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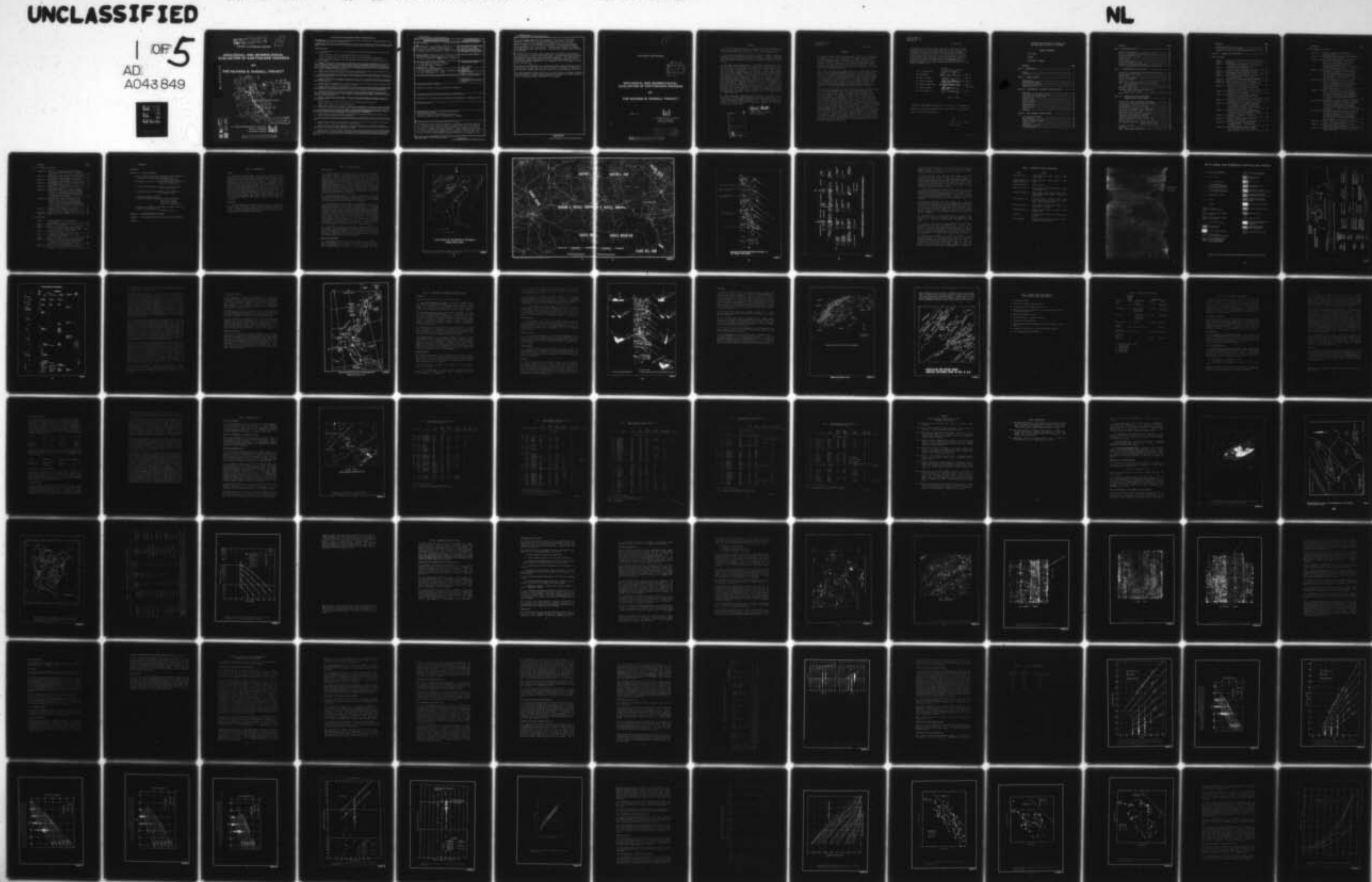
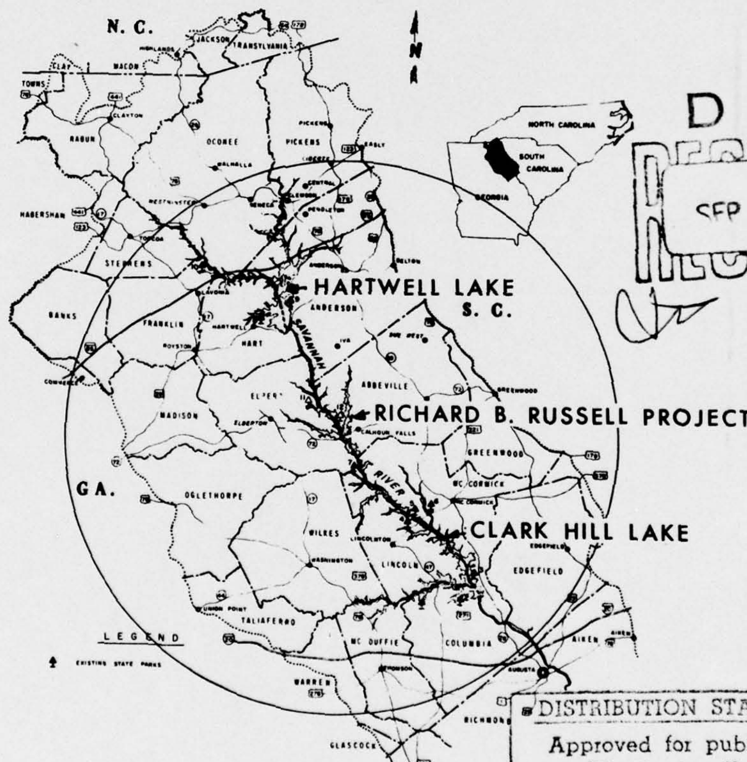


DESIGN EARTHQUAKE REPORT

GEOLOGICAL AND SEISMOLOGICAL EVALUATION OF EARTHQUAKE HAZARDS

AT

THE RICHARD B. RUSSELL PROJECT



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26

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4. TITLE (and Subtitle) Design Earthquake Report Geological and Seismological Evaluation of Earthquake Hazards at Richard B. Russell Project		5. TYPE OF REPORT & PERIOD COVERED Final Project Report April 1976 to April 1977
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Messrs. William E. Hancock, Earl F. Titcomb, Jr., Drs. Ellis L. Krinitzsky and Richard J. Lutton		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Engineer District, Savannah P. O. Box 889, ATTN: SASEN-FG Savannah, GA 31402		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 901 EN-FG
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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Seismic Risk, Zonation, Design Earthquake, Microearthquakes, Reservoir, Seismicity, Recurrence Rate, Savannah River, Piedmont

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

No evidence of active faults is present in the general area of the damsite. It is concluded that the faults which are present are all ancient ones and are inactive. Present day tectonism indicates that moderate earthquakes occur in the Piedmont and adjacent regions. Severe earthquakes are restricted to a narrow band along the Summerville to Charleston, South Carolina area. Motions attenuated from Summerville-Charleston band to the damsite are low.

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20. Four seismic risk zones were assigned. These are the Blue Ridge, Piedmont, Coastal Plain, and Charleston-Summerville Zones. The most severe condition is an earthquake at the damsite with a peak velocity of 30 to 45 cm/sec, 0.4 to 0.5g for acceleration, 20 cm approximate maximum for displacement, and 5 sec duration. For purposes of design, the maximum earthquake will occur under the dam. A group of time histories were selected for rescaling.

A probability of recurrence study showed that the operating earthquake has an acceleration of 0.075g (0.01 annual risk). The operating basis earthquake is generally more moderate than the maximum earthquake. It is selected on a probabilistic basis from regional and local geology and seismology studies as being the largest expected to occur during the life of the project; in this case, 100 years.

This peak ground acceleration is considerably smaller than the design value of the Richard B. Russell Dam. The dam is designed to withstand an earthquake several times stronger than would be expected to occur during its useful life.

The lake impounded by Russell Dam will not itself produce a damaging earthquake. Any earthquake or one that could conseivably be produced by the lake will not exceed the natural maximum earthquake for the region.

(1)

THE DESIGN EARTHQUAKE

GEOLOGICAL AND SEISMOLOGICAL EVALUATION OF EARTHQUAKE HAZARDS

AT

THE RICHARD B. RUSSELL PROJECT

MARCH 1977

U. S. ENGINEER DISTRICT, SAVANNAH
CORPS OF ENGINEERS
SAVANNAH, GEORGIA

FOREWORD

1. The U. S. Army Engineer District, Savannah (SAS) and the Waterways Experiment Station (WES) were authorized to conduct this study by the Directorate of Civil Works, Chief of Engineers, U. S. Army, Washington, DC.

2. This report was prepared in response to rapidly changing earthquake technology. This changing technology has prompted a proposed engineering regulation which will require assessment of earthquake hazards, including static and dynamic stability, in the design of certain new dams and existing dams.

3. The report was prepared by Drs. E. L. Krinitzsky and Richard J. Lutton (WES) and Mesrs. Earl F. Titcomb, Jr., and William E. Hancock (SAS). Consultants for this study were Rev. Louis Eisele, S.J., Spring Hill College, Dr. David T. Snow, Colorado School of Mines, Dr. Leland Timothy Long, Georgia Institute of Technology, Dr. Otto W. Nuttli, Saint Louis University, Dr. David B. Slemmons, University of Nevada, and Dr. Pradeep Talwani, University of South Carolina. The report dealing with analyses of earthquake recurrence in the region was prepared by Dr. C. Allin Cornell, Massachusetts Institute of Technology, a theoretical analysis of induced seismicity was prepared by Dr. David T. Snow, the upper bounds magnitude of the maximum "induced" earthquake, Clark Hill Lake area was prepared by Dr. L. Timothy Long. Thanks are extended to the numerous geologists who contributed ideas and resources to aid this study, in particular, Sam Pickering, Georgia State Geologist and Norman Olsen, South Carolina State Geologist, Dr. Villard S. Griffin, Jr., Dr. Robert D. Hatcher, Jr., Clemson University, David E. Howell, South Carolina State Development Board, Dr. Donald Secor, University of South Carolina, Drs. B. J. O'Connor and D. C. Prowell, U.S.G.S.

4. Also cooperating in the study was Mr. William K. Thompson, Chief, Foundation and Materials Branch, Savannah District, Dr. James Erwin, Division Geologist, South Atlantic Division, and Mr. Norman Dixon, Directorate of Civil Works Office, Chief of Engineers, U. S. Army, Washington, DC, Colonel G. H. Hilt, CE, and Mr. F. R. Brown were Director and Technical Director, WES, respectively.

Frank Walter

FRANK WALTER
Colonel, Corps of Engineers
District Engineer

REPORT SUMMARY AND
STATEMENT FROM THE
CONSULTANTS

17 March 1977

SUMMARY

No evidence of active faults is present in the general area of the Richard B. Russell damsite. It is concluded that the faults which are present are all ancient and inactive. Present day tectonism indicates that moderate earthquakes occur in the Piedmont and adjacent regions. Severe earthquakes have been restricted to the vicinity of Charleston, South Carolina. The faults are obscured by Coastal Plain sediments. Motions attenuated from Charleston to the Richard B. Russell damsite are low with the distance being about 170 miles.

Four seismic risk zones were assigned. These are the Blue Ridge, Piedmont, Coastal Plain, and Charleston-Summerville zones. The peak motions for bedrock were determined by the panel to be accelerations of 0.4 to 0.5g, velocities of 30 to 45 cm/sec and displacements up to approximately 20 cm, with a 5 sec duration. At the Richard B. Russell site, this corresponds to a magnitude of 5.5 on the Richter scale. (Design earthquakes define the ground motion at the site of the structure and form the bases for dynamic response analyses. Generally, several design earthquakes are investigated, for both the maximum earthquake and the operating basis schedule.) A group of time histories were selected for rescaling.

For purposes of design, the most conservative (the safest) approach assumes that the maximum earthquake (the severest earthquake believed to be possible at a site on the basis of geological and seismological data) will occur under the dam. Though a maximum induced earthquake can be postulated, equal to the maximum seen in the historic seismicity over comparable portions of eastern United States, there are no reliable and proven methods within the present state-of-the-art to predict whether or not an induced earthquake will occur. The study by Dr. Snow shows that the geologic stress field at the project site is compatable with initiating activity. The historic record for the large number of reservoirs in eastern United States shows that only a small percentage of the reservoirs (4 of 59 in the Piedmont) may have induced activity and those earthquakes have a maximum magnitude of 4.5. The analysis of Dr. Long suggests that a maximum induced earthquake for the Piedmont is about magnitude 5.6. If seismicity were induced near the reservoir, the experience shown in 4 of 59 Piedmont reservoir areas, indicates the maximum magnitude would be much lower than 5.5, probably in the 3.5 to 4.5 range. Consequently, for the purpose of dam safety and design, a conservative analysis is to assume that an induced earthquake will occur, and it will have a maximum magnitude of 5.5, with a shallow hypocenter at the damsite.

REPORT SUMMARY AND
STATEMENT FROM THE
CONSULTANTS

17 March 1977

A probability of recurrence study showed that the operating earthquake has an acceleration of 0.075g (0.01 annual risk). The operating basis earthquake is generally more moderate than the maximum earthquake. It is selected on a probabilistic basis from regional and local geology and seismology studies as being likely to occur during the life of the project; in this case, 100 years. In this instance, this peak ground acceleration is considerably smaller than the design value of the Richard B. Russell Dam. In other words, the dam ~~is~~ WILL BE designed to withstand an earthquake several times stronger than would be likely to occur during its useful life.

Dr. C. Allen Cornell	Absentia See statement of consultant in lieu of attendance	
Dr. David T Snow	David T Snow	17 Mar 77
Dr. Otto W. Nuttli	Otto W. Nuttli	17 Mar 77
Dr. David B. Slemmons	David B Slemmons	17 Mar 77
Dr. Leland Timothy Long	Leland Timothy Long	17 Mar 77
Dr. Pradeep Talwani	Talwani	19 March '77
Fr. Louis Eisele, S. J.	L. J. Eisele, S.J.	17 Mar 77

March 22, 1977

I approve of the summary with respect to its accuracy in reflecting the material on seismic risk analysis which I contributed as a consultant to the U.S. Army Corps of Engineers.

C. Allin Cornell

C. Allin Cornell

GEOLOGICAL AND SEISMOLOGICAL FACTORS AND THE SELECTION OF THE DESIGN EARTHQUAKES

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PART I - INTRODUCTION

General

1. The Richard B. Russell Damsite is 170 miles from the intense earthquake which occurred in 1886 at Charleston, South Carolina, and approximately 19 miles from the nearest sizable local earthquake which occurred in 1875 near Lincolnton, Georgia. The historic record, dating back to 1698, includes seventeen moderate earthquakes within the Savannah River Basin above the Fall Line. Approximately 16 earthquakes of intensity greater than Modified Mercalli V (MM- Scale) have occurred in the Piedmont and Blue Ridge seismotectonic provinces as defined by Hadley and Devine (1974). Although the seismicity of a 50-mile radius area around the damsite has been very moderate, the two most severe events only produced damage to the most poorly built and badly designed structures. The Richard B. Russell Damsite was carefully evaluated for seismic risk because it falls within Seismic Zone 2 of Algermissen (1969) and the great severity of the Charleston earthquake.

Objectives

2. This study undertook to provide a review of the tectonism, faulting and present activity of faults, earthquake recurrence, question of induced seismicity, and the significance of the seismic history in the region. Design Earthquakes were determined along with their appropriate ground motion for bedrock at the damsite.

PART II - GENERAL GEOLOGY

Physiography

3. The Richard B. Russell Dam and Lake is sited in the Piedmont Physiographic Province. The general relation of the site to the Piedmont, Coastal Plain and Appalachian Mountains is shown in Figure 1. The terrain is broadly rolling but generally the surface decends gently towards the south and southeastward with the valley of the Savannah River. This upland surface is the Washington Plateau in Georgia (LaForge 1925), the Laurens slope of South Carolina, or the Winder Slope (Clark and Ziza, 1977). Rounded stream divides have approximate elevations of 700 to 1,000 feet m.s.l. and narrow, shallow valley bottoms have elevations of 350 to 500 feet m.s.l. A few monadnock hills have relief approaching 100 to 200 feet above the general terrain (e.g. Parsons Mtn., Little Mtn.). Such knobs have been explained by greater resistance to erosion.

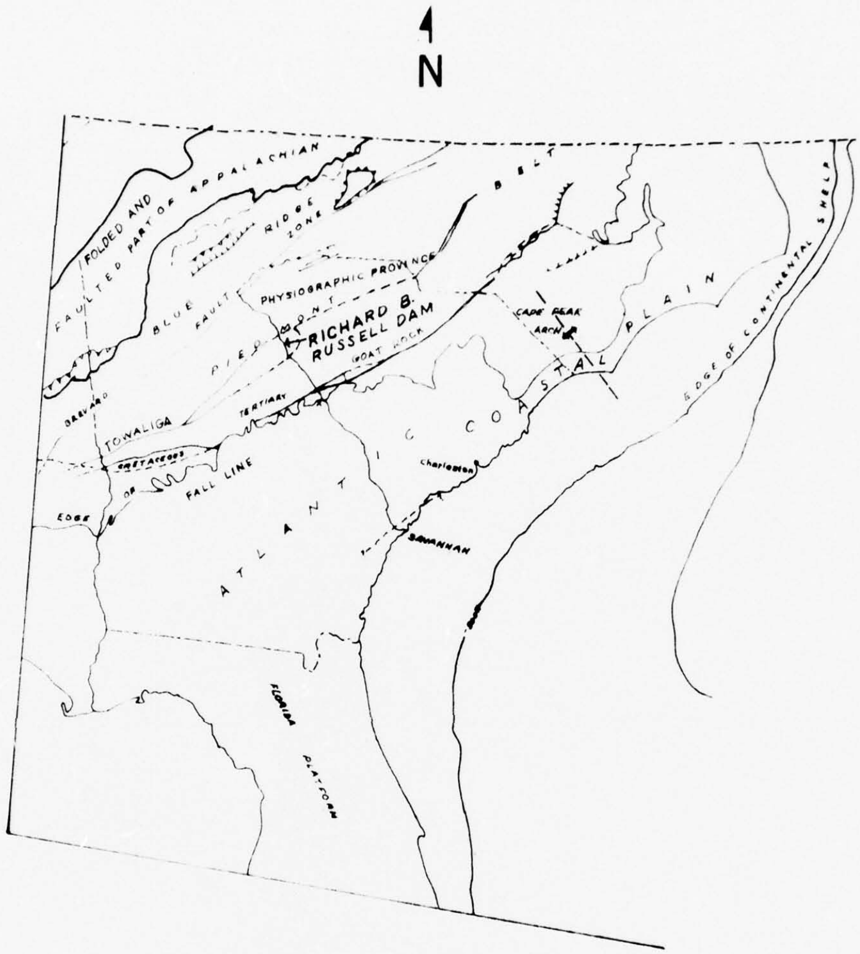
4. The Savannah River and its tributaries, Broad River and Rocky River, make up the major drainage system (Figure 2). The Savannah drainage is bordered by the headwater tributaries of the Oconee River on the southwest and the Saluda River on the northeast.

5. The overall pattern of the network is apparently a result of superimposed drainage. Major streams southeast of the Brevard Zone (Figure 1) are dendritic, while along and northwest of the Chauga belt, steams have a trellis drainage related to underlying geological structure. Staheli (1976) believes that in the southeastern Piedmont, consequent streams developed a dendritic drainage on a Coastal Plain surface of Oligocene time. Since this time, they have been superpositioned across Piedmont rocks. Many believe there is little validity in the concept of peneplanation in the development of the Piedmont upland surface. Crustal instability in the southern Appalachian Mountains has prevented peneplanation from occurring. It should remain an open possibility that the land has responded to other unexplored factors in developing the accordant ridges and drainage patterns.

6. A few small stream terraces found in this study along Clark Hill Lake and the riparian Savannah River indicate through the presence of kaolin clayey gravel and sand overlain by manganese nodular saprolite that the terrace material may have been of greater antiquity than Pliestocene. Manganese nodular saprolite has been though to be as old as Cretaceous and as young as early Pliestocene.

Regional Stratigraphy

7. Stratigraphy in this area is poorly understood due largely to intense metamorphism, lack of marker beds, complex folding and faulting and saprolization. (See Figures 3, 4, and 6 for the stratigraphy.) Accordingly, this review has relied principally upon work



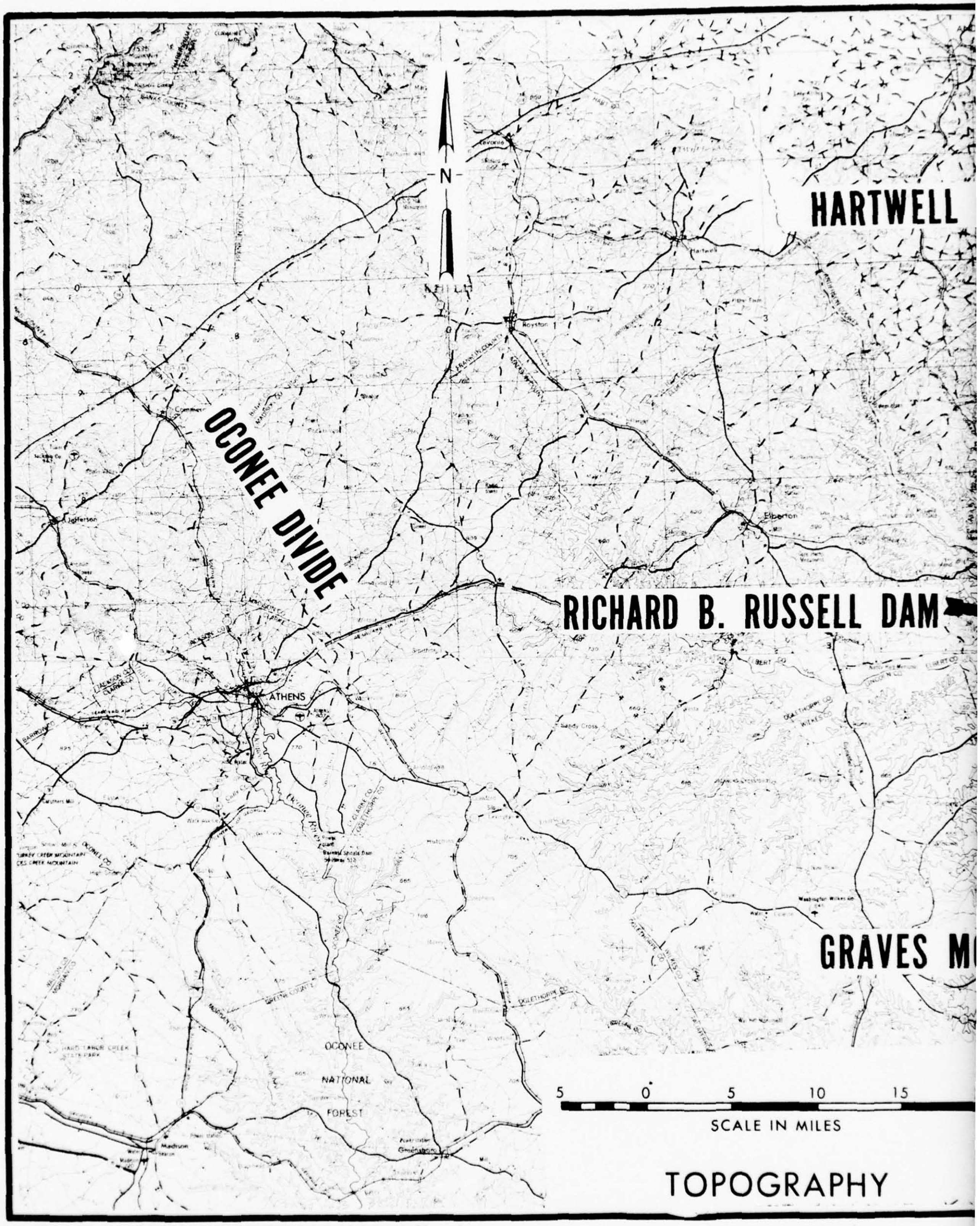
SCALE 1:5,000,000

50 0 50 100 150 200 MILES

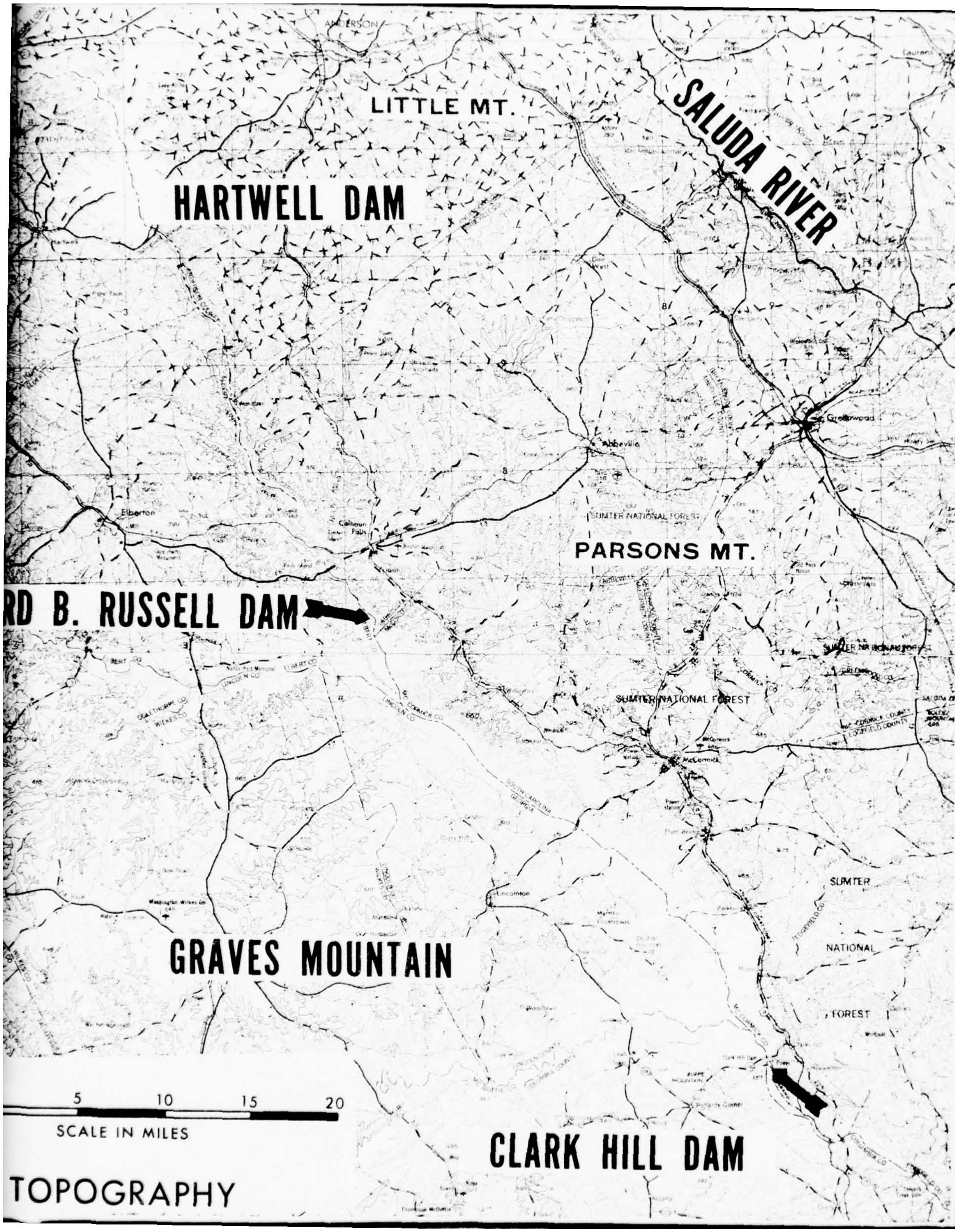
LOCATION OF RICHARD B. RUSSELL DAM AND LAKE

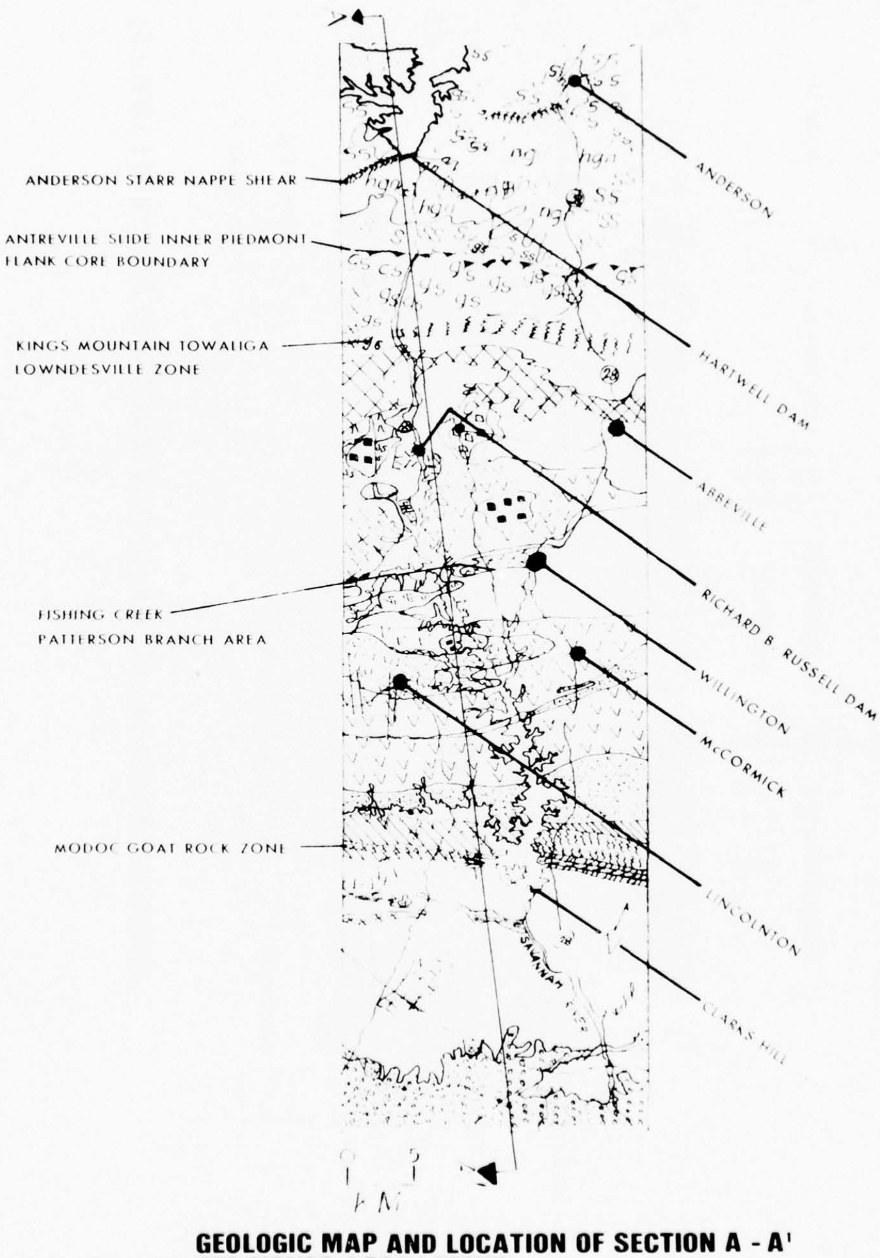
ADAPTED FROM SEISMOTECTONIC MAP OF THE EASTERN UNITED STATES

FIGURE 1



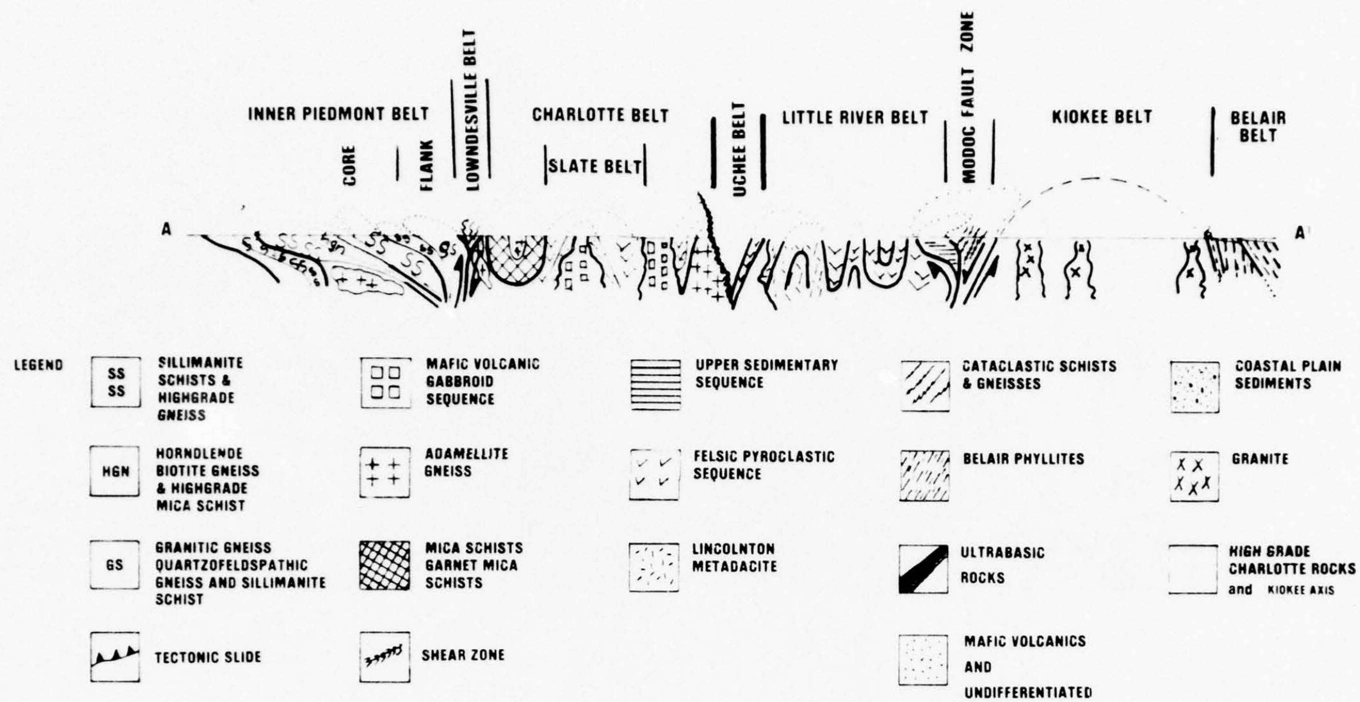
ADAPTED FROM USGS 2 DEGREE SHEETS ATHENS, GA. & GREENVILLE, SC


LITTLE MT.
SALUDA RIVER
HARTWELL DAM
PARSONS MT.
RD B. RUSSELL DAM
SUMTER NATIONAL FOREST
GRAVES MOUNTAIN
SUMTER
NATIONAL
FOREST
5 10 15 20
SCALE IN MILES
CLARK HILL DAM
TOPOGRAPHY



GEOLOGIC MAP AND LOCATION OF SECTION A - A'
SEE FIGURE 4 FOR LEGEND

FIGURE 3.



INTERPRETIVE CROSS SECTION A - A' (FOR LOCATION OF SECTION SEE FIGURE 3)

FIGURE 4.

listed in Table 1. Stratigraphy is presented in terms of lithology as opposed to formational names because of the lack of detailed stratigraphic information. Additional stratigraphy was developed in field studies and is used in this report.

8. Figure 5 and Maps 1 and 2 (maps 1 and 2 are missing from insert pocket) illustrate the general geology. The section consists of approximately 124 km. (412,000 feet) of metamorphosed sedimentary and volcanic rocks intruded by granite, gabbro, and serpentine and possessing highly mobilized cores of gneiss with migmatitic flanks. Metavolcanic rocks intruded by gabbro and injected by gneiss are the predominant rocks in the immediate vicinity of the damsite. The geologic ages range from Precambrian to Permian.

9. The age relationships of the parent rocks in the various recognized belts are shown in Figure 6. Overstreet (1970) states that the metamorphosed sedimentary and volcanic rocks in the Carolina Slate, (Figure 4) Charlotte, Kings Mountain-Lowndesville, and Inner Piedmont belts consist of three stratigraphic sequences separated by two unconformities. These sequences mainly contain graywacke, shale, tuff and lava.

Each sequence was considered to have been deposited in a subsiding basin with the western parts of all three sequences superimposed. Near the Brevard zone and extending more or less southeastward, these sequences persist to at least the continental shelf. Sundelius (1970) feels that rocks of the Carolina Slate belt, were derived from nearby volcanic islands and tectonic ridges by deposition in intervening basins. A synopsis of time relationships of various strata and events is given in Figure 7.

10. Proceeding northwest from the Coastal Plain, the youngest pertinent stratum is the Late Cretaceous Tuscaloosa Formation. This clastic unit is comprised of kaolin-bearing, crossbedded sands and gravel.

11. Occurring as discontinuous erosional remnants, below the Tuscaloosa Formation at the edge of the Piedmont (near Augusta) is the phyllite of the Belair belt. Saprolite developed on the surface in the Belair belt has been preserved by the Cretaceous burial. The Belair belt is composed of metavolcanic tuff and argillite and is thought to be equivalent to the Little River Series occurring further northwest (paragraph 13). The Belair belt is probably Cambrian in age.

12. The Kiokee belt, exposed west of the Fall Line (Figure 1), is the oldest in the study area. The age is thought to be late Precambrian or early Paleozoic. In South Carolina, rocks of the Kiokee belt are amphibolites and granitic gneiss, whereas in Georgia, the rocks are felsic gneiss derived from igneous rocks, quartzites, and other gneisses. During Ordovician time, a younger adamellite locally intruded into the belt. Two periods of metamorphism are recognized in

TABLE 1 - REFERENCES IN STUDY OF STRATIGRAPHY

Area	Author
Hart County, GA	Grant (1958); Baker (1933); Corps of Engineers (1960)
Anderson County, SC & Pickens County, SC	Griffin (1974a, b, 1972b; 1971a, b; 1970, 1969)
Abbeville County, SC	Griffin (1972a)
Elbert County, GA	Austin (1968, 1965); Chandler (1972); Penley and Sandrock (1973)
McCormick County, SC	Medlen (1968); Griffin (1972a); Secor (1977); Johnson (1970a); Bell (1966); Overstreet & Bell (1965a)
Lincoln County, GA	Crawford (1968a); Crickmay (1952); Fouts (1966); Paris (1976); Peyton & Cofer (1950); Hurst, Crawford & Sandy (1966)
Wilkes County, GA	Peyton and Cofer (1950); Fouts (1966); Crawford (1968a); Cook (1966)
Columbia County, GA	McLemore (1965); O'Connor & Prowell (1976); Daniels (1974)
Edgefield	Johnson (1970b); Daniels (1974); Pirkle (per. com 1976)
General Region	Overstreet & Bell (1965a); Crickmay (1952); Georgia Geol. Survey (1976)

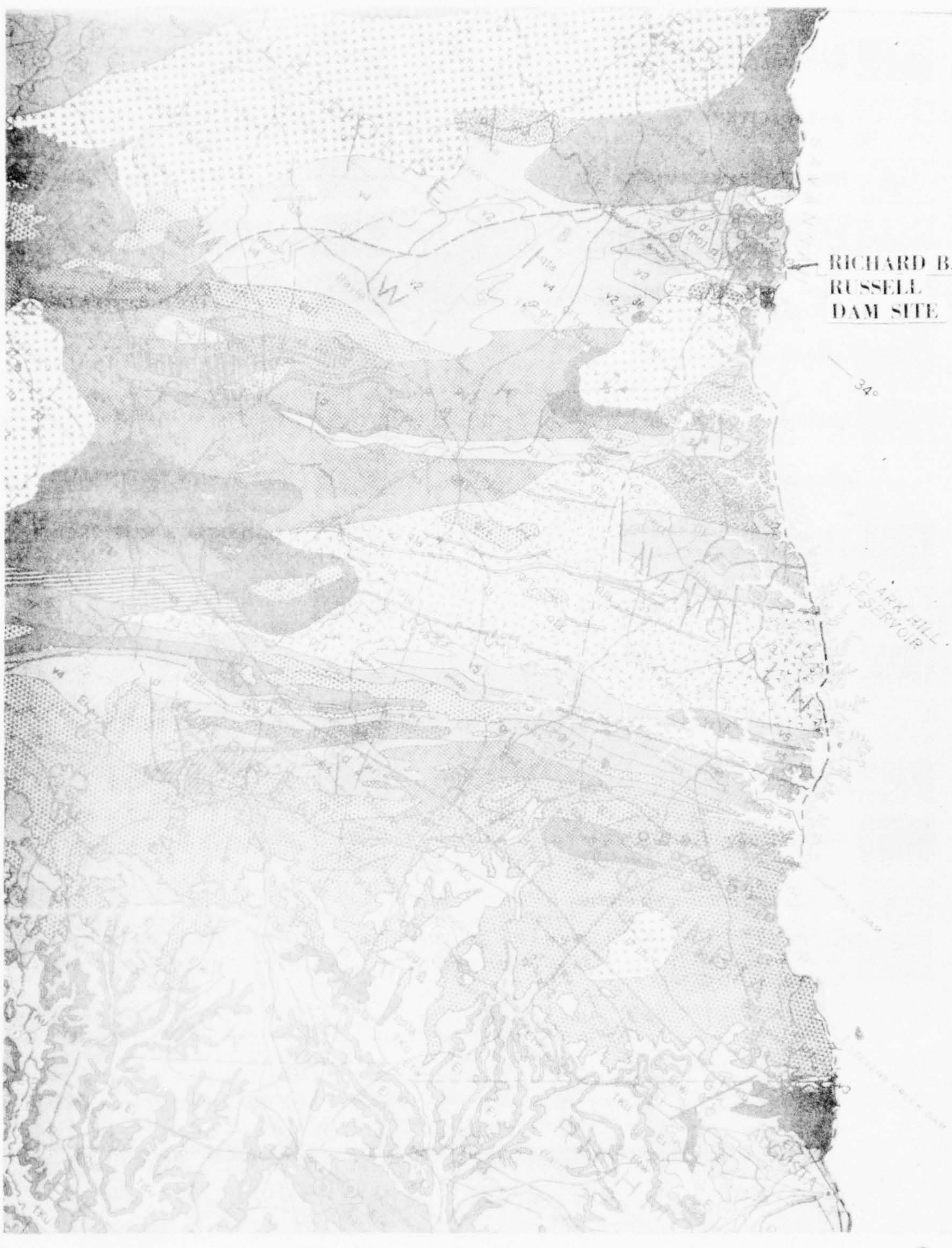


Figure 5 Portion of the Geologic Map of Georgia

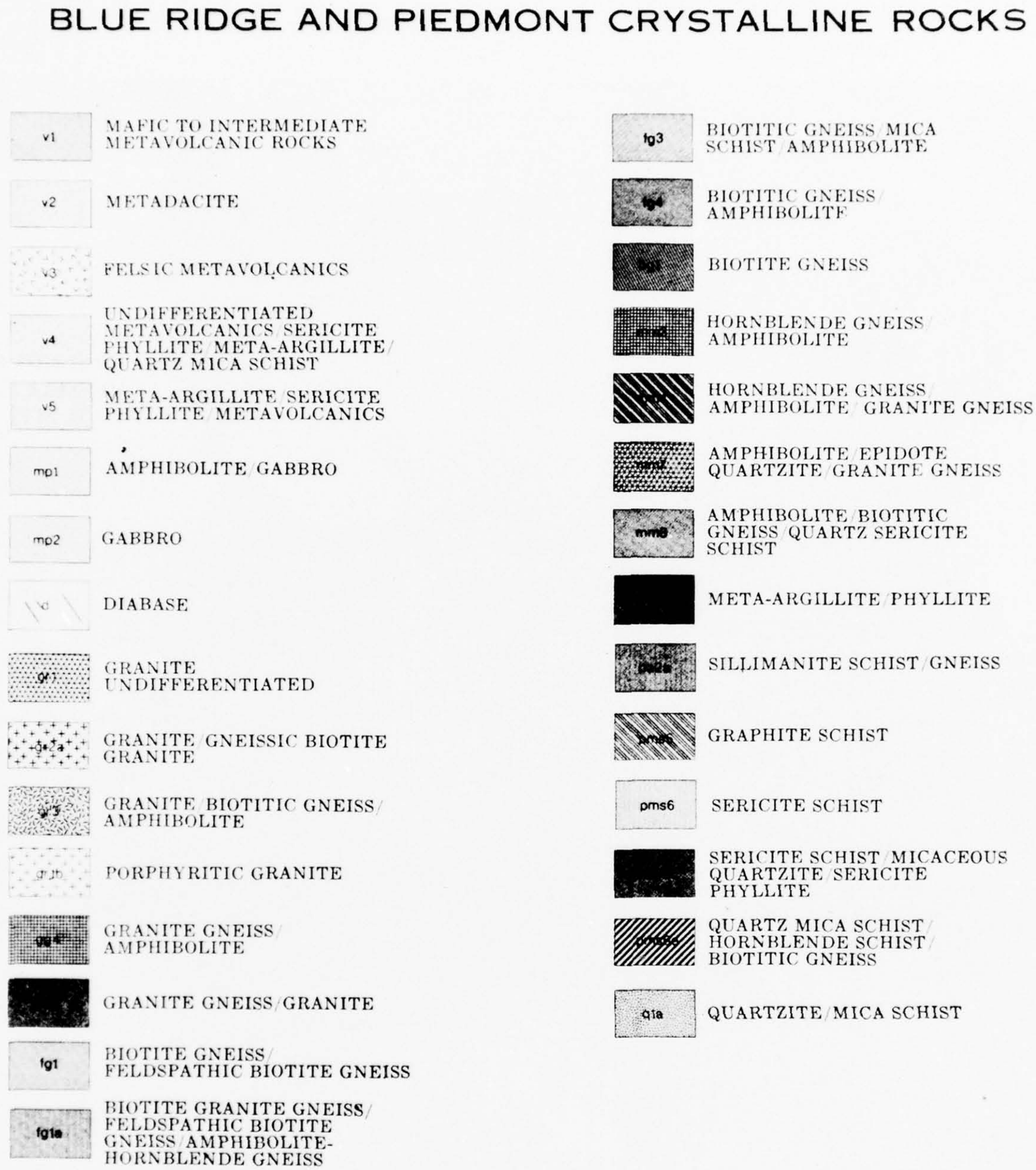
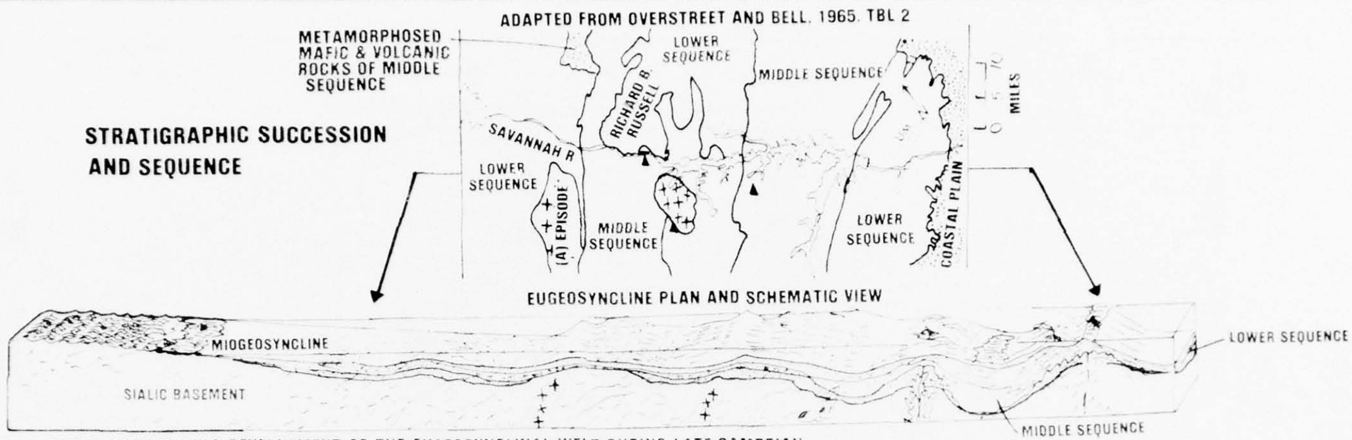


Figure 5 Portion of the geologic map of Georgia (Georgia Geological Survey, 1976).

STRATIGRAPHIC SUCCESSION AND SEQUENCE



BLOCK ILLUSTRATING DEVELOPMENT OF THE EUGEOSYNCLINAL WELT DURING LATE CAMBRIAN

INFERRED GEOLOGIC AGE	SEQUENCES OF SEDIMENTARY AND PYROCLASTIC ROCKS AND INTRUSIVE EPISODES	INNER PIEDMONT BELT	KINGS MOUNTAIN BELT	CHARLOTTE BELT	CAROLINA SLATE BELT
PERMIAN AND CARBONIFEROUS	INTRUSIVE EPISODE C	GABBRO, PYROXENITE, AND NORITE MUSCOVITE PEGMATITE	SYENITE GABBRO AND PYROXENITE	SYENITE, GABBRO, PYROXENITE, AND NORITE GRANITE IN CIRCULAR PLUTONS	SYENITE, GABBRO, PYROXENITE, AND NORITE GRANITE IN CIRCULAR PLUTONS
	UPPER SEQUENCE				
			UNCONFORMITY		
	MIDDLE SEQUENCE	BIOTITE GRANITE GNEISS			
DEVONIAN THROUGH ORDOVICIAN	MIDDLE SEQUENCE	BIOTITE SCHIST (IN PART) QUARTZITE (IN PART) BIOTITE GNEISS AND HORNBLENDE GNEISS (IN PART)	SERICITE SCHIST (IN PART) HORNBLENDE SCHIST	MICA GNEISS (IN PART)	ARGILLITE (IN PART) MUSCOVITE SCHIST (IN PART) QUARTZITE QUARTZ-MICROCLINE GNEISS AMPHIBOLITE
			UNCONFORMITY		
	INTRUSIVE EPISODE A	BIOTITE GNEISS AT IVA, ANDERSON COUNTY	NOT RECOGNIZED	PORPHYRITIC GRANITE IN ABBEVILLE COUNTY AND GNEISSIC GRANODIORITE IN YORK COUNTY	NOT RECOGNIZED
CAMBRIAN AND LATE PRECAMBRIAN	LOWER SEQUENCE	HORNBLENDE GNEISS (IN PART) BIOTITE SCHIST (IN PART) BIOTITE GNEISS AND MIGMATITE (IN PART)	GRANITOID GNEISS	GRANITOID GNEISS	GRANITOID GNEISS
			UNCONFORMITY (NOT OBSERVED IN PIEDMONT)		
	BASEMENT		UNOBSERVED IN PIEDMONT		

FIGURE 6

STRATIGRAPHIC RELATIONSHIPS

ERA	PERIOD	AGE AT BASE OF PERIOD, MY	PIEDMONT — ROCK SEQUENCES: GEORGIA	PIEDMONT — ROCK SEQUENCES: SOUTH CAROLINA	PIEDMONT — INTRUSIVE SEQUENCE	PIEDMONT — METAMORPHIC EVENTS	OUTSIDE 50 MILE RADIUS OF DAM
CENOZOIC	TERTIARY	65					
MESOZOIC	CRETACEOUS	136	TUSCALOOSA *FORMATION*	TUSCALOOSA *FORMATION*	FLINTY *CRUSHED ROCK*		
MESOZOIC	JURASSIC	195					VALLEY AND RIDGE
MESOZOIC	TRIASSIC	225	GRABEN BASIN FILL	GRABEN BASIN FILL	DIABASE DIKES		
	PERMIAN					METAMORPHIC EVENT	
	PENNSYLVANIAN	280					
	MISSISSIPPIAN	345					
PALEOZOIC	DEVONIAN — LATE		RHYOLITE FLOWS AND DIKES				
PALEOZOIC	DEVONIAN — MIDDLE						
PALEOZOIC	DEVONIAN — EARLY	395			GOSHEN GRANITE	METAMORPHIC EVENT	BLUE RIDGE
PALEOZOIC	SILURIAN	437	WACKE CONGLOMERATE SEQUENCE		GABBRO, DIORITE SYENITE COMPLEXES ELBERT GRANITE		
PALEOZOIC	ORDOVICIAN — LATE					METAMORPHIC AND DEFORMATIONAL EVENT	
PALEOZOIC	ORDOVICIAN — MIDDLE						
PALEOZOIC	ORDOVICIAN — EARLY	500	LITTLE RIVER SERIES: UPPER SEDIMENTARY SEQUENCE	BELAIR BELT	MEDIUM GRAINED ADAMELLITE		
PALEOZOIC	CAMBRIAN — LATE						
PALEOZOIC	CAMBRIAN — MIDDLE		FELSIC PYROCLASTIC SEQUENCE				
PALEOZOIC	CAMBRIAN — EARLY	570	LINCOLNTON METADACITE				CHAUGA BELT
PRECAMBRIAN	LATE		KINGS MOUNTAIN (WACOOCHEE) BELT; DADEVILLE BELT; INNER PIEDMONT	LOWNDESVILLE; KINGS MOUNTAIN BELT; INNER PIEDMONT	SERPENTINE & ULTRABASIC TABULAR BODIES		
PRECAMBRIAN	MID	800	UCHEE BELT; KIOKEE BELT	*CHARLOTTE BELT*; KIOKEE BELT	COARSE GRAINED ADAMELLITE STOCKS	INTENSE *METAMORPHIC* EVENT	

FIGURE 7

the Kiokee belt. A severe event during the Precambrian affected the Kiokee belt only. There was a less intense event, probably during late Ordovician to Silurian time.

13. Northwest of the Kiokee belt and overlying it are the Paleozoic rocks of the Carolina Slate belt, and its equivalent in Georgia, the Little River Series. Radiometric dates as old as 560-570 million years have been obtained in the Little River Series (Carpenter, 1976). This sequence is metadacite whose parent was a series of volcanic flows and tuffs. Two main bodies of metadacite lie in the study area, one centered around Lincolnton, Georgia, and the second around the Russell Damsite. Overlying the metadacite is an pyroclastic sequence of tuffs, agglomerates, welded tuffs, felsic and mafic flows interfingered with volcanic graywacke and argillite. Overlying the pyroclastic sequence is an upper sedimentary sequence consisting of banded argillite and volcanics. The youngest sequence is well exposed northwest of the Modoc fault zone in South Carolina. Granitic Intrusions in the Little River Series, such as Goshen Granite, is 365 million years old (Paris, 1976).

14. The Little River Series overlies the Charlotte belt to the northwest. The Charlotte belt in South Carolina consists of gneiss and schist derived from older igneous rocks, graywacke, shale, tuff, and volcanics. In Georgia, the Charlotte belt includes large areas of granitoid gneiss, high-grade schist and amphibolite derived from sedimentary rocks and igneous plutons. The Charlotte belt is Precambrian to Cambrian in age. The exact stratigraphic relationship between the Charlotte and Slate belt in the study area is uncertain because the boundary is poorly defined. Certain relationships indicate that metamorphic grade is the only distinction. Locally, the Charlotte belt rocks form the centers of regional anticlines, and they are believed to be older than the flanking Slate belt; however, units unrelated by simple stratigraphy exist along shear zones and faults.

15. The relationship of the Charlotte belt and Inner Piedmont belt (Figure 4) to the Kings Mountain-Lowndesville belt is also not clear. In South Carolina, the Kings Mountain belt separates the Inner Piedmont from the Charlotte belt and is thought to be younger, perhaps in the nature of a detachment zone squeezed between adjacent older blocks. Accordingly, the Kings Mountain belt overlies the Inner Piedmont, and the adjacent Charlotte belt. The Lowndesville belt does not extend into Georgia. As the Lowndesville belt crosses the Savannah River, foliation and bedding wrap around the nose of the syncline and the belt pinches out (Griffin, 1976, personal communication). The Inner Piedmont mica schist, gneiss, quartzite, and amphibolite of South Carolina do not display any clear significance in Georgia and may be obscured by faults (Hurst, 1970).

16. A minor event occurred also within the region 380-386 M.Y.B.P. with the intrusion of gabbro and associated chloritization of the complexes in the Slate, Charlotte and Inner Piedmont belts. Medlin (1968) finds alteration, cataclastic deformation and tilting in such complexes.

Lithology Near the Site:

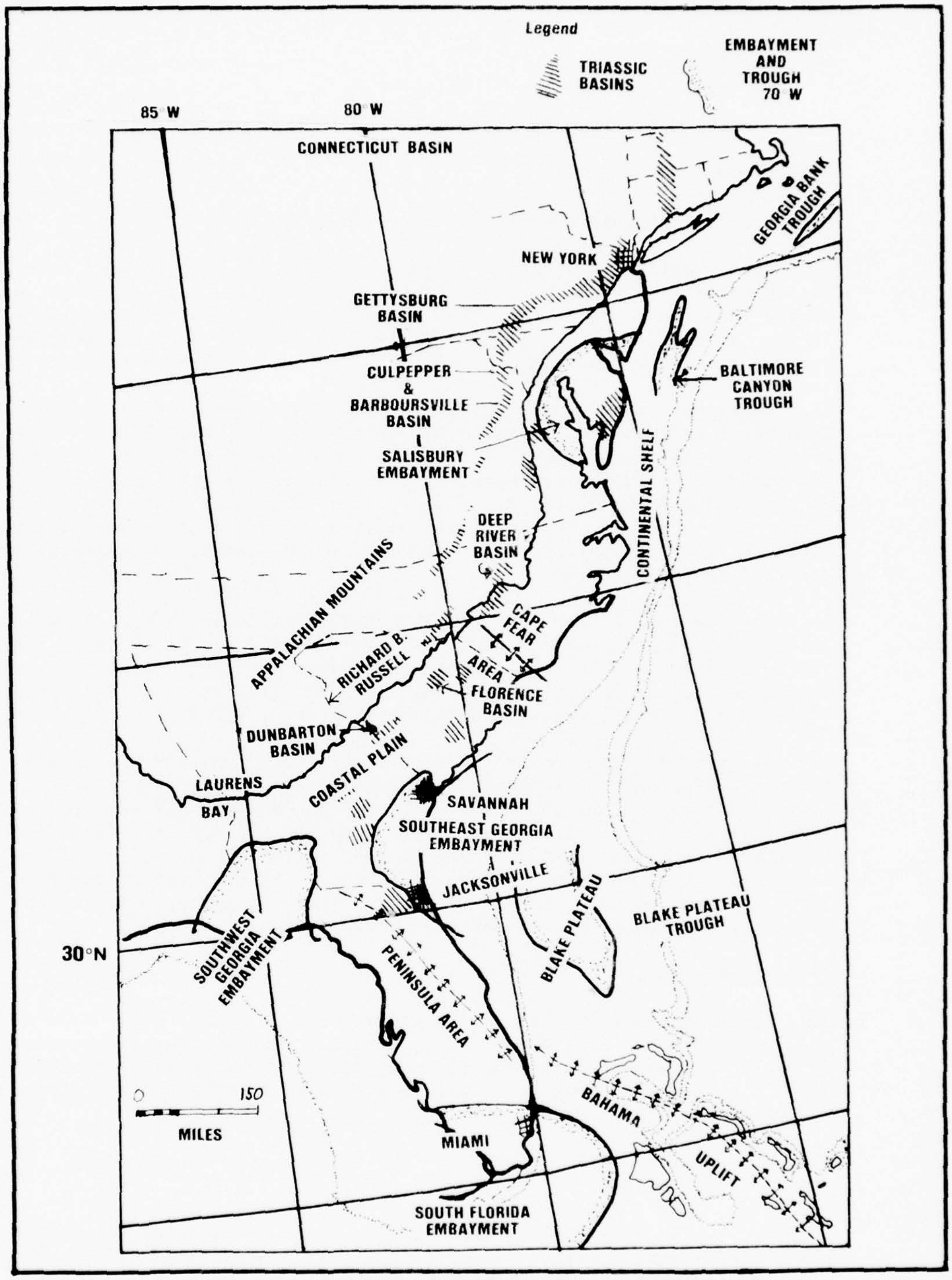
17. The rocks in the study area have been subjected to various degrees of metamorphism. Adjacent to the damsite, they are intermediate in metamorphic grade. Both regional and contact types of metamorphism are evident. The metadacite adjacent to the dam is upper greenschist grade. Contact hornfels most probably surrounds the Calhoun Falls gabbro complex, buc little evidence is found of contact metamorphism near the damsite. Pervasive gabbroic dikes, however, are hydrothermally altered to chlorite schist.

18. Downstream of the damsite, along Clark Hill Lake, the Slate belt rocks are generally greenschist grade and exhibit less metamorphic alteration. Upstream of the damsite, metamorphic grade increases, although the Lowndesville belt also shows retrograde metamorphism.

19. The fine-grained rocks exhibit well-developed foliation and slaty cleavage. They have been metamorphosed into slates and phyllites. Coarser clastics and mafic flows have been transformed into granitoid gneiss and amphibolite. The Inner Piedmont is separated by a discontinuity between quartzofeldspathic gneiss and the higher grade sillimanite schist, gneiss and amphibolite. In cataclastic zones, all rocks are crenulated and broken with some evidence of retrogression.

Depositional History:

20. The rocks in the region resulted from deposition in a eugeosynclinal basin. The source area undergoing erosion supplied clastic material to a marginal basin much as present-day sources supply embayments (Figure 8). During early to mid-Precambrian time, and intense metamorphic and compressional event transformed the eugeosyncline into the present late Precambrian basement of the Appalachians. In late Precambrian time, a second clastic source area appeared. This source contributed volcanic rocks and volcanoclastic sediments and is identified as an island arch-trench subduction system by Carpenter (1976), Hatcher (1972), and others.



Map of the Atlantic Coastal Plain and Continental Shelf **FIGURE 8**

Adapted from Marine, 1974

PART III - PRECAMBRIAN AND PALEOZOIC TECTONIC HISTORY

Orogenies.

21. Ancient orogenic events have occurred as follows.

22. Post Grenville-Adirondack History. During the Precambrian, there was deposition in eugeosynclinal basins with clastics derived from a source land represented by Grenville-Adirondack Mountains (Fisher 1970). Also, clastic sediments were derived from a late Precambrian seaward source representing a geanticlinal welt or volcanic islands.

23. Pretaconic and Taconic Cycle. During the Precambrian to middle Ordovician deformation and metamorphism of the eugeosynclinal track occurred. Following uplift, erosion occurred during the Ordovician and intrusion of magma accompanied the Paleozoic compressional phase. By the late Ordovician or Silurian, large overthrust sheets moved slices of deformed geosynclinal sediments toward the northwest. Southern Appalachian rocks remained high while marine transgression occurred in the interior.

24. Acadian Cycle. The Acadian cycle was a late Devonian to Permian phase of compression accompanied by continued deposition from the rising mountain source. The Towaliga, Brevard and Goat Rock faults were generated during this phase, as were the folds and faults in the Valley and Ridge and Cumberland Plateau (Hatcher, 1972).

25. Triassic Events. After the Acadian orogeny, considerable erosion followed uplift of the southern Appalachian region. During the Triassic, this region was subjected to tensional forces which resulted in normal faulting and development of grabens. These fault-bounded structures received clastic sediments from adjacent highlands. Associated with sedimentation in the grabens were basalt intrusions and flows. In some basins, normal faulting shows greater displacement along the southeast than the northwest boundaries.

Fold Deformation.

26. Structural deformation in the study area involved both folding and faulting. The axis of the folds generally run southwest-northeast as do the strikes of major faults. The dip of the foliation and bedding is quite steep, and it is uncommon to find bedding and foliation planes dipping less than 50 degrees.

27. The folding style observed in the study area or reported by others is as follows:

a. In the Belair belt, the style is one of shallow northeast plunging folds with steep isoclinal limbs. Generally, limbs are steeply dipping to the southeast.

b. In the Little River Series, the predominate fold style is a series of vertical isoclinal folds with gentle plunge to the northeast, in some cases with evidence of polyphase folding, as, for example, on the Modoc fault zone.

c. The fold style in the Kiokee belt is determined by a broad anticline. However, at the mesoscopic level, rocks have been tightly folded with steep to moderately steep dips. Along the northwestern limb, the rocks have undergone polyphase folding. Multiple phases of folding dominate contacts of both Slate and Kiokee belt rocks.

d. In the Carolina Slate belt (Howell and Pirkle, 1977), top-bottom criteria indicate a regional syncline, with its axis northwest of Parksville, South Carolina, in the argillite. The axis trends N 50°E and plunges 10°N. Fold styles within the bounding fault zone at Modoc include isoclinal folds and drag folds. Fold style from Parksville, South Carolina, to the northwest flank are cylindroidal.

Charlotte Belt.

e. The Charlotte belt consists of southwest plunging assymetrical folds overturned to the west-northwest. Also present are tight northeast striking isoclinal folds. Griffin (1972a) states that, in South Carolina, the fold style in the Charlotte belt is problematical because of poor exposure. The style appears to be one of upright folded isoclines.

Lowndesville Belt.

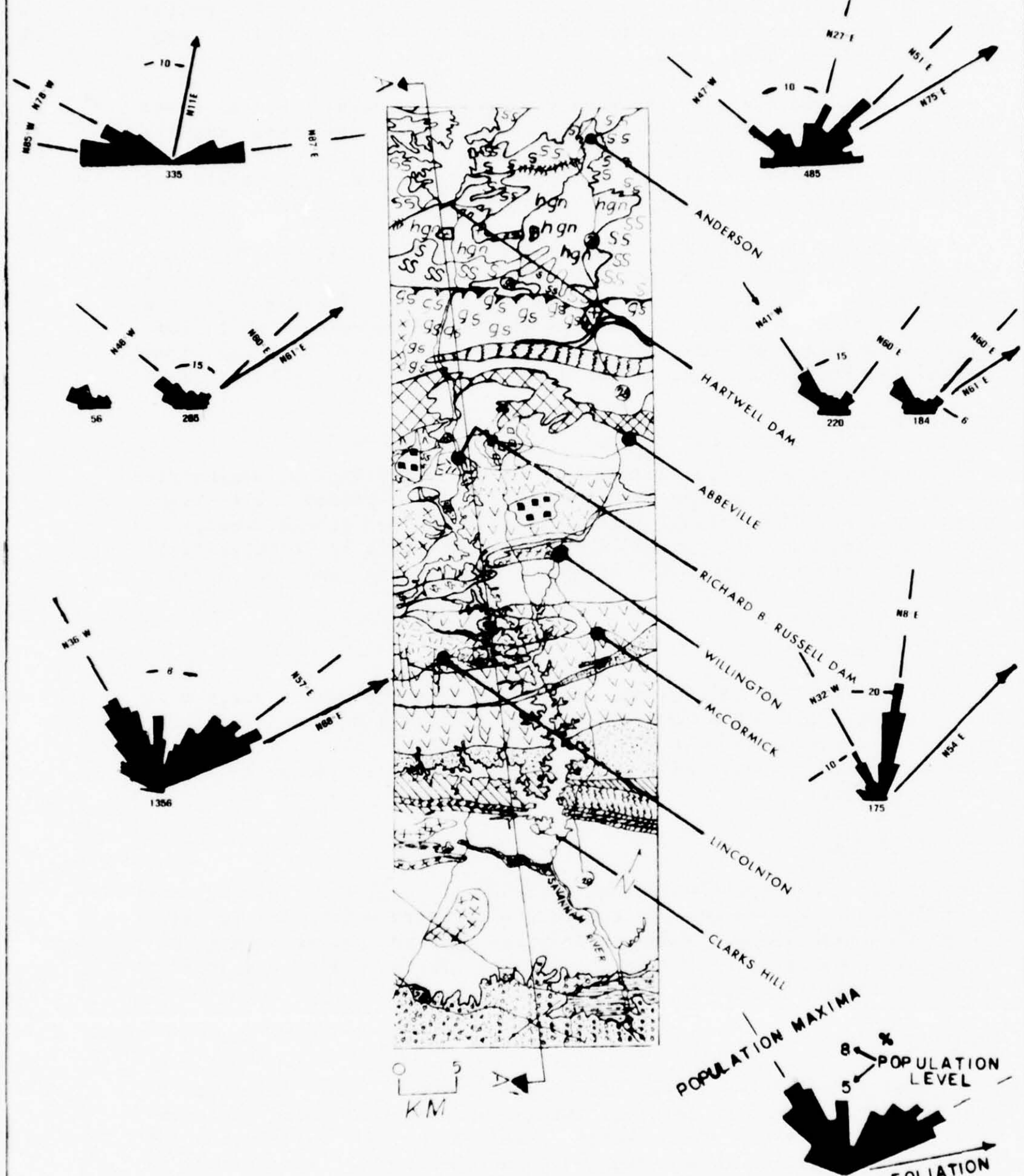
f. Griffin (1972a) believes the pattern in the Lowndesville belt folds is suggestive of a general syncline including many small, tight, upright isoclines. The belt ends near the Savannah River, where the folds plunge to the northeast at 10 degrees. The belt suggests cylindroidal folding.

Inner Piedmont.

g. Griffin (1972a) shows the attitude of foliation within the Inner Piedmont core to steepen toward the boundary separating it from the southeastern flank. Moderate to steep dips predominate along the core while moderate dips are on the flanks. The core also has locally steeper northwest dips.

Jointing.

28. Measured patterns in the study area suggest that jointing is geometrically related to folding. Figure 9 summarizes joint orientations within the study area. Field examination and correlation of joints with foliation show maxima of joint trends that correspond to foliation maxima. Two clear maxima of joints lie at N 35°W and N 50-55°E. After extracting the joint maxima corresponding to folding, the remaining pattern suggests compressional and extensional axes oriented N 80-85°W and N 8-10°E, respectively.



No. of measurements

Jointing in the Savannah River Study Area

Populations are plotted for each five degrees in the Northern semicircle

FIGURE 9

Faulting.

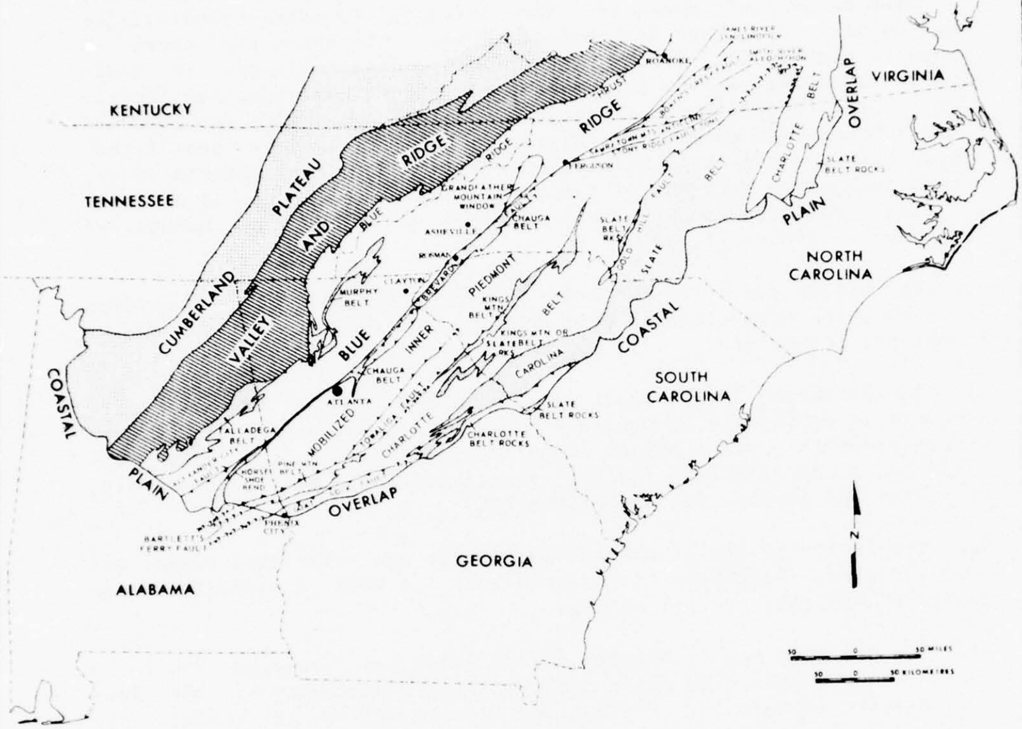
29. Table 3, Figures 10 and 11 list mapped faults in the study area. The three major fault zones are the Brevard, Towaliga-Lowndesville-Kings Mountain, and Goat Rock-Modoc. These fault zones are shown on Figure 10 with Table 2 listing their field characteristics. In addition to the above faults, there are other significant features identified by Griffin (1972a) as tectonic slides. These slides are observed to mark boundaries or discontinuities in the stratigraphy and lithology. Evidence for their existence includes silicified breccia zones, abrupt changes in attitude of foliation, and discontinuity in metamorphic and lithologic facies. Their inferred locations and boundaries are shown in Figure 11.

30. The Belair fault located near Augusta, Georgia, is a reverse fault on which metavolcanics have been carried up against the younger Tuscaloosa Formation.

31. The Patterson Branch fault is interpreted to be a normal fault. Although an earthquake of moderate magnitude occurred near this fault, it has shown no surface offset along its 7-1/4 km length. The criteria for classification include stratigraphic field relationship, trenching and geophysical investigation.

32. The faults in the Lincolnton metadacite and associated rocks are normal faults. Geophysical and field evidence used to classify these faults showed they are not active.

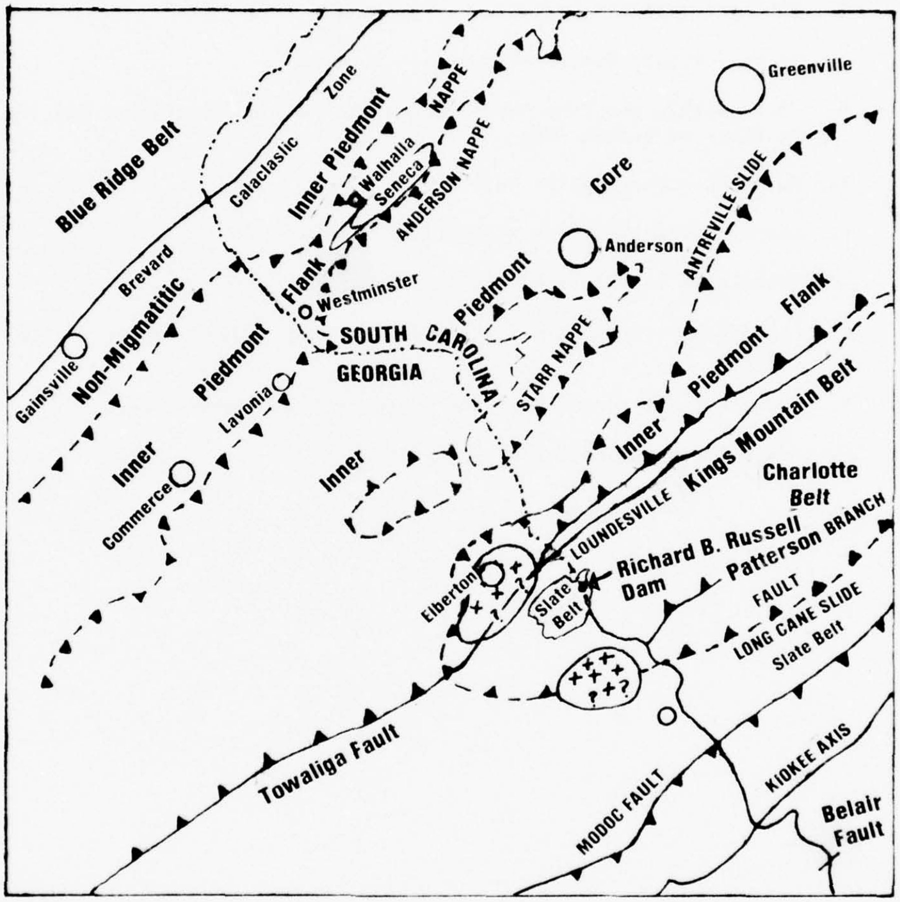
33. The Geologic Map of Georgia (1976) shows the Towaliga Fault to splay into branches with one branch positioned northwest of the Russell Damsite (Figure 5). Field investigation failed to confirm the location as mapped by Penley and Sandrock (1973). It is suggested that in the Elbert County area, the Towaliga Fault is obscured by the Elbert Granite body and the Charlotte-Slate belt boundary (Figure 11).



MAJOR TECTONIC ZONES IN THE PIEDMONT

Adapted from Hatcher (1972) **FIGURE 10**

Sketch tectonic map of the Greenville 1:250,000 U.S. Geol. Sur. two degree sheet The Brevard Zone in Georgia is adapted from SMITH & GREEN (1968) and in South Carolina from HATCHER (1969 b). The position of the Carolina slate belt outliers is modified from OVERSTREET & BELL (1965, Pl. 2), slides are from GRIFFIN (1971 d) and additional boundaries are by HANCOCK.



FAULTS IN THE STUDY AREA
SKETCH TECTONIC MAP OF GA. & S.C.

FIGURE 11

TABLE 2 - BREVARD, MODOC, AND LOWNDESVILLE DUCTILE MYLONITIC ZONE CHARACTERISTICS

1. Topographic Lineament

2. Straight with Slightly Curved Segments

3. SE to Vertical Dip - Lowndesville Dips NW

4. Rocks Within the Zone Subjected to the Same Deformational History as Those on Either Side

5. Multiple Stratigraphic Units

6. Contain Cataclastic or Mylonitic Features

7. Cataclasis in Differing Units

8. Barrovian Metamorphism Retrograded to Green Schist-Facies Assemblages

9. Fundamental Structures of the Southern Appalachian Orogen

10. Zones Change Character by Splaying

TABLE 3 - FAULTS IN THE STUDY AREA

FAULT	MINIMUM MAPPED LENGTH (MI)	FAULT TYPE	PROBABLE AGE (MAX)	PROBABLE AGE (MIN)
Modoc	79	1. Thrust 2. Strike-slip	Paleozoic	Late Devonian to Permian
Loundesville	160	Questionable Right Lateral Strike-Slip	Paleozoic	Late Devonian to Permian
Brevard	450	1. Right Lateral Strike-Slip 2. Dominantly Dip-Slip	Paleozoic	Late Devonian to Permian
Belair Fault	13	Reverse	50 M.Y.B.P.	Quaternary
Patterson Branch	4-1/2	Normal or Thrust		Mesozoic
Diversion Channel Fault	4/10	Thrust	355 M.Y.B.P.	270 M.Y.B.P.
Lincolnton Type Metadacite	1		Normal	598 M.Y.B.P.

1. Howell and Perkle (1976)
2. Hatcher (1972)
3. Hatcher (1974)
4. USGS (1976)
5. Secor (1977)
6. Paris (1976)

PART IV - POST-PALEOZOIC STRESS HISTORY

34. Indicators of post-Paleozoic stress included the following: Triassic basin faulting, Jurassic diabase dikes and flows, siliceous ultramylonite dikes (flinty crushed rocks), joints, and isostatic rebound. A change from a compressive field at the end of the Paleozoic to an extensional field during the Mesozoic is suggested by the first three indicators. The Cenozoic record indicates a later return to compressive tectonics in at least some portions of the Appalachians. However, conflicting data in the southern Appalachians cloud a clear reconstruction of stress. The Tertiary seems to be transitional between types of stress fields.

Fault Basin Development.

35. Triassic tensional forces resulted in normal faulting and development of grabens from Georgia to Canada (Figure 8). Grabens received clastic sediments from the adjacent highlands. Basalt intrusions and flows occur also in these basins. Known Triassic basins include Laurens Conty basin, Dunbarton basin, and Florence basin. Since the bounding normal faults parallel to the Appalachian trend, the axis of extension is thought to have been perpendicular to the Appalachians.

Dike Formation.

36. The extensional field continued throughout the Mesozoic. The pattern of Appalachian diabase dikes has been cited (May 1971) as evidence of extension during the break-up of North America, West Africa and South America. Accordingly, the dikes represent lines of tension in the stress field imposed on the continental crust at the onset of North American seafloor spreading.

Flinty Crushed Rock Zones.

37. Post-diabase dike age siliceous ultramylonite breccia dikes (FCR) occur throughout the Piedmont and Blue Ridge provinces of the southern Appalachian. These FCR dikes have been the subject of inconclusive writings by White (1950), Conley and Drummon (1965), Hatcher (1974), Haselton (1974), Birkhead (1973), and others, who, despite many differences, mostly agreed that these features are:

a. Post-orogenic and post-diabase in age;
b. Are extensional in origin;
c. Do not seem to offset contacts horizontally, but do vertically.

Examples include the Blue Ridge front on a grand scale and the Patterson Branch fault on a smaller scale. Presently, these FCR dikes are taken to indicate late Mesozoic to early Tertiary extension.

Cenozoic Uplift.

38. White (1950) has suggested the Blue Ridge front to be a border fault of a Triassic basin reactivated during the Tertiary by normal faulting, but presently extensively modified by erosion. Haselton (1974) agrees that the geological setting of the Blue Ridge front suggests it is a fault scarp. He supplements White's original argument with nine additional points. Some objection to the evidence has been raised by Hatcher (1974), chiefly because detailed mapping in some areas where the front passes does not indicate faulting.

39. Meyerhoff (1972) indicates that although late Triassic faulting was a factor in determining the boundary between the Blue Ridge and Piedmont provinces, it did not alter the general direction or pattern of the drainage. This pattern is believed to have been set by the Permian deformation with western flowing streams in the south (Tennessee River system) and southeast flowing streams in the north (Susquehanna River). The local superposition of the eastern flowing streams has taken place with a western shift in the Mesozoic drainage divide initiated by late Triassic faulting which lowered the base elevation of the Piedmont. Sapping of the Blue Ridge front effected an ever increasing northwestern migration of the divide by stream capture. Intermittent uplift and tilting centered around the presistently high Blue Ridge constantly keeps the eastern gradients higher than the western. Although this conclusion is not established as fact, it does suggest a continued extensional field in the Mesozoic, Tertiary and possibly into the Quaternary.

40. A partial return to compressional tectonics in the southern Appalachians during the Quaternary may be supported by overthrust features such as the Belair fault. The most recent statement released by the Department of Interior Geological Survey* indicates activity along the fault in the past 50 M.Y.B.P., but disavows claims for Quaternary movement. Two other such features have been identified by Drennen (1950) and by Howell and Zupan (1974).

Jointing.

41. Systematic measurements of jointing in the crystalline rocks of the Savannah River drainage confirm two major trends (Figure 9) with one probably related to extensional stress. Maxima between N 10°W to N 10°E are suggested to indicate shear, but of pre-Quaternary age. As in most joint studies, however, the exact age of jointing is difficult to determine, and jointing may represent remnant stress rather than contemporary pattern.

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*Hereafter, the Department of Interior, Geological Survey will be shown as USGS.

Contemporary Stresses.

42. Contemporary compressive stress for the Appalachian region has been suggested by Sbar and Sykes (1973). They infer that eastern North America is under high horizontal stress. Principal stress is oriented north to northeasterly, as seen in hydrofraction overcoring and focal plane solutions. However, the results in the Appalachians south of the middle Atlantic states show considerable scatter and hence may not be reliable. The nearest measurements to the study area are at Lithonia, Georgia, and Bad Creek pump storage site in South Carolina. Hooker and Johnson (1969) and Hooker and Duval (1966) found in Georgia the following data:

Location	Bars σ_1	Ratio σ_1/σ_2	Trend of σ_1	Rock Type
Lithonia	102	1.5	N 8° E	Granite
Lithonia	111	1.7	N49° E	Gneiss
Douglasville	35	1.8	N64° E	Gneiss

Haimson (1976) hydrofracting at Bad Creek Pump Storage Site in a near surface hole on moderate to steep slopes found $\sigma 1$ to be northeasterly and $\sigma 3$ vertical. Recent fault plane solutions for earthquakes indicate the following:

Location	Mechanism	Compression	/ Dilation	
Charleston, SC	Thrust Fault	NE	NW	1.
Willington, SC	Normal	Ambiguous		2.
	Strike-Slip	E-W	N-S	

1. Tar (1976); 2. Talwani (1976).

The preceding data allows Snow (1977, this volume) to deduce the southeast to be a region of high horizontal stress; however, other authors (Sbar & Sykes, 1973, 1974, and Hooker, 1966, 1967) find that total available information suggests that south of eastern middle Atlantic states stress field indicators and measurements inconsistently demonstrate high horizontal stress.

Isostatic Rebound.

43. Isostatic rebound of the southern Appalachians has to be considered in analysis of current stress. At the end of mountain building, the southern Appalachians are believed to have stood over a considerably thickened crust. Mathur (1971) considers the crustal mantle boundary to be at 41 km depth under the Piedmont. Conservatively, from the end of the tectonic compressional phase during the

Paleozoic, the Appalachian system has lost 3 km elevation and shed 20 km from its root through rebound. The immense volume of clastics (over 21 km) now lies in the Coastal Plan and continental margin.

44. Late tectonic movements within the Appalachians probably are recorded best in the sediment record (Owens, 1970; Meyerhoff, 1972). Uplift in the source land is recorded in the depositional basin in quantities of clastics that depend upon the intensity of the uplift and basin warping. Owens (1970) finds the carbonate facies reaching its maximum onlap in Florida, Georgia, and South Carolina in the Oligocene overlap. This is a period of quiescence in the source region. During the Miocene, the Coastal Plain record shows the Cape Fear arch (Figure 1) barring the northward transgression. Clastic units are thickest in old troughs such as the Suwannee straits, indicating reactivation during a period of renewed uplift in the south Appalachians.

45. The last recorded major tectonic uplift was the epierogenic uplift of the whole Atlantic Coastal Plain and Piedmont, probably starting in the late Pliocene. Although large scale eustatic rise and fall of sea level continued through the Pleistocene, a continued emergence is recorded in older coarse clastics, standing higher than the young Pleistocene deposits. The Pliocene to Quaternary deposits of coarse clastics derived from the southern Appalachians are thin, which suggests waning intensity to the uplift.

46. Staheli (1976) utilizes the absence of clastic facies among Oligocene sediments to indicate that sedimentation must have extended inland as far as the Brevard zone during a major Oligiocene transgression. Coastal facies have evidently been eroded away during renewed uplift. Cramer (1974) and Eames (1962) also bring out the same relationship in the Cenozoic rocks of Georgia and the Gulf Coast. Mather and Applin (1971) find evidence for increasing seaward tilt of the margin and coastal plain in the sediment thickness and depositional record preserved in the basins and flanks of the Atlantic arches and rises. Isostatic uplift of the Appalachians accompanied by erosion and subsequent deposition on the margins has apparently been of sufficient intensity to shift mass centers towards the margins and to cause tilting and down warping of the Coastal Plain. Uplift and tilting of the southeastern flank can be a possible mechanism for continued contemporary extension centered around the Blue Ridge, while the significantly high horizontal stress reported by Sbar and Sykes (1973) continue to deform the Coastal Plain. The western underflow of the mantle combined with isostatic rebound of the Appalachian mass could be responsible for buckling of the margins and shear failure of local rigid bodies, such as reported by Long (1976) under the Coastal Plain.

PART V -EARTHQUAKE ACTIVITY

Historic Earthquakes

47. The distribution of historic earthquakes in the general region of the Richard B. Russell site is shown in Figure 12. The earthquakes are listed by state of origin in Table 4 along with their dates, coordinates, intensity, source of data, and other information. Intensity is in Modified Mercalli (MM) units for the severest shaking. An abridged statement of the MM scale is contained in Figure 13.

Relation of Earthquakes to Geologic Structures

48. Historic earthquakes in the area of Figure 12 have not been related to specific geological structures or to known faults. None of the earthquakes has had recognizable surface displacement. Despite the considerable study, particularly in the Charleston-Summerville area, relationships between earthquakes and subsurface to basement geology have not been developed.

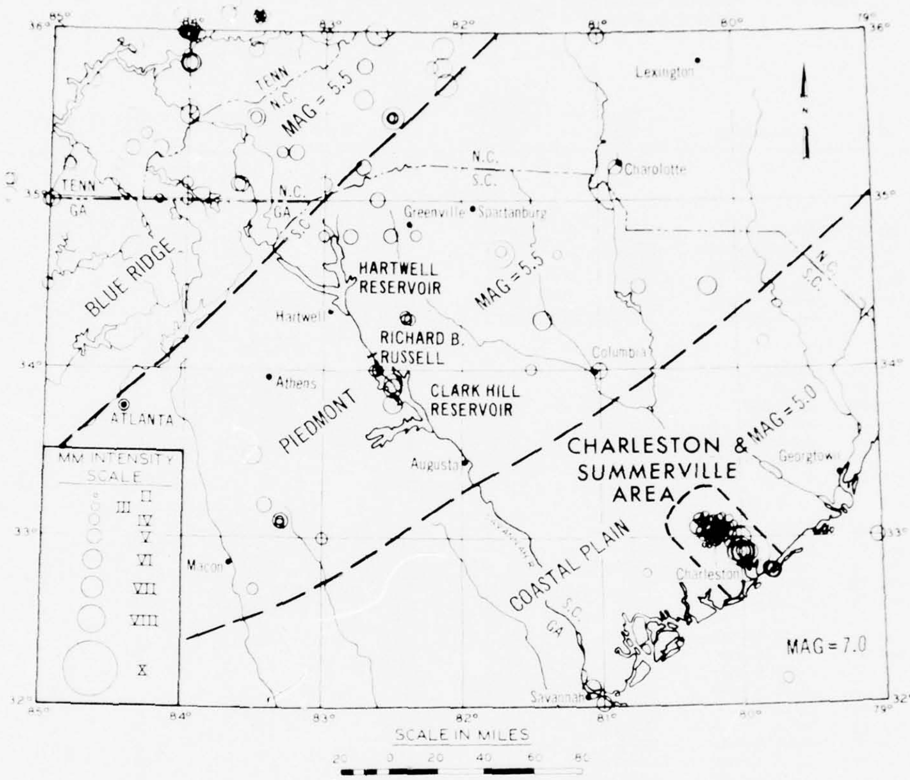
Principal Earthquake Zones

49. Figure 12 shows earthquake epicenter and seismic zones in the region. The Richard B. Russell project, as well as the Clark Hill and Hartwell Lakes, are in the Piedmont zone. Adjacent zones are Blue Ridge and Coastal Plain. The Charleston-Summerville (South Carolina) zone encompasses the small area of intense seismicity that is localized in this small portion of the Coastal Plain. The earthquakes are those in Table 4 for Charleston and Summerville, South Carolina.

50. The Piedmont is largely a region of metamorphosed rocks. The Blue Ridge, with its folded sedimentary series, bounds the Piedmont along the Brevard fault zone in the Savannah River basin. The Coastal Plain represents young, gently dipping sedimentary rocks. Its boundary with the Piedmont is somewhat inexact. The Fall Line, usually taken as the boundary, is not directly tectonic. The boundary chosen for this study is along a zero gravity line which was mapped passing through the area below Augusta, Georgia. Choosing this boundary was somewhat arbitrary yet more relatable to tectonism in terms of bring to an end the influence of the Piedmont crystalline rocks rather than Cretaceous-Tertiary deposition and subsequent erosion. Coastal Plain sediments formerly onlapped into what is now the Piedmont.

51. Thus, the principal zones, in a general way, are related to physiographic provinces. The Charleston-Summerville area, however, is unique. At Charleston-Summerville, there is a concentration of seismic activity which is not observed anywhere else in the Coastal Plain.

52. Earthquakes in the Blue Ridge, Piedmont, Coastal Plain, and Charleston-Summerville zones, because they cannot be related to specific faults, are assumed to occur anywhere in their respective zones. Thus, the zones are interpreted as carrying "floating" earthquakes.



SEISMIC ZONATION AROUND PROJECT SITE

Occurrence of Earthquakes and Seismic Zonation in the General Region of the Richard B. Russell Site.

FIGURE 12

Table 4 Historic Earthquakes in the General Region of the Richard B. Russell Project Site

Year	Date	Locality	Time EST	North Latitude deg	West Longitude deg	Intensity* MM	Source of Data**		
							VPISU	EHUS	Other
				GEORGIA					
1872	Jun 17	Milledgeville	1500	33.1	83.3	V	X	X	
1875	Jul 28	Milledgeville	1805	33.1	83.3	III	X		
	Nov 01	GA-SC border	2155	33.8	82.5	VI	X	X	
1884	Mar 31	Milledgeville	0500	33.1	83.3	III	X		
1885	Oct 17	Sandersville	1730	33	83	IV	X		
1902	Oct 18	SE TN-NW GA	1300 & 1700	35.0	85.3	V	X	X	
1903	Jan 23	GA-SC	2015	32.1	81.1	VI	X	X	
1909	Oct 08	NW GA	0500	35	85	IV-V	X		
1912	Jun 20	Savannah		32	81	V	X		
	Oct 22	Dublin	2015	32.7	83.5	IV	X		
1913	Mar 13	Calhoun-Gordon Counties	0000	34.5	85	IV	X		
1914	Mar 05	Atlanta	1505	33.5	83.5	VI	X	X	
1933	Jun 09	Eatonton	0630	33.3	83.3	(seismic?)	X		
1935	Jan 01	NC-GA border	0315	35.1	83.6	V	X	X	
1936	Jan 01	NC-GA border	0300	35	84.2	III	X		
1940	Oct 19	TN-GA border	0055	35	85	IV	X		
1943	Jul 28	Augusta	2330	33.4	82.0	(seismic?)	X		
1947	Dec 27	TN-GA border	1900	35	85.3	IV	X		
1958	Apr 08	Tift County	1200	31.5	83.5		X		
1963	Oct 08	GA-SC border	0601:43.4	34.2	82.7		X		
1964	Feb 18	GA-AL border	0432:11.6	34.8	85.5	V/4.4	X	X	
	Mar 07	Elberton	1803:00.1	34.1	82.8	(Blast?)	X		
	Mar 12	Macon	2020:18	33.2	83.4	V/4.4	X	X	
1965	Apr 06	GA-SC border	2119	34.0	82.5		X		
	Apr 07	GA-SC border	0741:10.2	33.8	82.5		X		
	Jul 22	Sandersville	2355:33.3	33	83		X		
	Nov 08	Canton	1258:01.0	34.2	84.6		X		
	Nov 08	Canton	1304:11.5	34.2	84.6		X		
1969	Nov 04	Greensboro	1858:23	33.6	83.3	(Blast?)	X		
	Nov 05	Greensboro	2217:5	33.6	83.3	(Aftershock?)	X		
	Nov 07	Greensboro	2052	33.6	83.3	(Aftershock?)	X		
1974	Aug 02	GA-SC border	0852:09.8	33.9	82.5	VI/4.8	X		

* Magnitude indicated as appropriate.

** VPISU - Virginia Polytechnic Institute and State University, 1975.
EHUS - "Earthquake History of the United States, Pub. 414, NOAA, 1973.

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Table 4 **Historic Earthquakes in the General Region of the Richard B. Russell Project Site**

Year	Date	Locality	Time EST	North Latitude deg	West Longitude deg	Intensity* MM	Source of Data** VPISU	EHUS	Other
				SOUTH CAROLINA					
1698	Feb								
1754	May 19	Charleston	(May 12?)	32.8	79.8		X		
1776	Nov								
1799	Apr 04	Charleston		32.8	79.8		X		
	Apr 11	Camden	0320	34.3	80.6		X		
	Apr 11	Camden	1655	34.3	80.6		X		
1843	Feb 07	Charleston	1000	32.8	79.8		X		
1857	Dec 19	Charleston	0904	32.8	79.8	VI	X	X	
1860	Oct	Charleston		32.8	79.8		X		
1869	Summer								
1876	Dec 12	Charleston	PM	32.8	79.8		X		
1879	Oct 26	Winnsboro		34.4	81.1		X		
1886	Spring								
1886	Jun	Charleston		32.8	79.8		X		
	Aug 27	Summerville	0130	33.0	80.2		X		
		Summerville	0830	33.0	80.2	V?	X		
	Aug 28	Summerville	0530	33.0	80.2		X		
	Aug 29	Summerville		33.0	80.2		X		
	Aug 31	Charleston	2151 & 2159	32.9	80.0	IX-X	X		EN (1975) Nuttli (1976)
	Oct 22	Charleston	0520	32.9	80.0	VI	X	X	
	Oct 22	Charleston	1445	32.9	80.0	VII	X	X	
	Nov 05	Charleston	1220	32.9	80.0	VI	X	X	
1906	Aug 05	Summerville	0102	33.0	80.2		X		
1907	Apr 19	Charleston	0330	32.8	79.8	IV-V	X	X	
1908	Jan 15	Summerville	1400	33.0	80.2	III-IV	X		
			(Another shock one minute later)						
	Mar 03	Summerville	1606	33.0	80.2	III-IV	X		
1908	Mar 07	Summerville	0150	33.0	80.2	III-IV	X		
	Oct 25	Summerville	2310	33.0	80.2	III	X		
	Oct 28	Summerville	0624	33.0	80.2	III-IV	X		
	Dec 28	Summerville	0624	33.0	80.2	III-IV	X		
1909	Feb 25	Summerville	2300	33.0	80.2		X		
	Aug 21	Summerville	0836	33.0	80.2		X		
	Dec 14	Summerville	1800	33.0	80.2		X		
1910	May 02	Summerville	0415	33.0	80.2		X		
	Sep 02	Summerville	0218	33.0	80.2		X		
	Sep 12	Summerville	1529	33.0	80.2		X		
1911	Apr 20	NC-SC border	2200-2300	35.2	82.7	V	X	X	
	Nov 24	Charleston	0717	32.8	79.8		X		

* Magnitude indicated as appropriate.

** VPISU - Virginia Polytechnic Institute and State University, 1975.
EHUS - "Earthquake History of the United States, Pub. 414, NOAA, 1973.

Note: Source data: EN - Earthquake Notes, Vol 46, 1975.

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Table 4 **Historic Earthquakes in the General Region of the Richard B. Russell Project Site**

Year	Date	Locality	Time EST	North Latitude deg	West Longitude deg	Intensity* MM	Source of Data** VPISU	EHUS	Other
				SOUTH CAROLINA (continued)					
1912	Mar 31	Charleston	1525	32.8	79.8		X		
	Jun 12	Summerville	0530	32.9	80.0	VI-VIII(VII)	X	X	EN(1975)
	Jun 29	Summerville	----	32.9	80.0		X		
	Aug 30	Summerville	1152	32.9	80.0		X		
	Sep 29	Summerville	0306	32.9	80.0		X		
	Nov 17	Summerville	0730	32.9	80.0		X		
	Nov 25	Summerville	2232	32.9	80.0		X		
	Dec 07	Union County	1410	34.7	81.7	III-IV	X		
	Dec 15	Summerville	1154	32.9	80.2		X		
1913	Jan 01	Union County	1328	34.7	81.7	VII-VIII (1)	X	X	
	Jan 25	Summerville	1937	32.9	80.2		X		
	Feb 05	Summerville	1606	32.9	80.2		X		
	Mar 09	Summerville	1130	32.9	80.2		X		
	Jun 06	Summerville	1320	32.9	80.2		X		
1914	Mar 06	Darlington & Florence	2020	34.2	79.8	III-IV	X		
	Mar 06	Chester	1530	34.7	81.3	III	X		
	May 31	Walterboro	2303	32.8	80.7	III	X		
	Jun 19	Summerville	0303	33.0	80.2	III	X		
	Jul 13	Summerville	2053	33.0	80.2	IV	X		
	Jul 14	Summerville	0300	33.0	80.2	II	X		
	Sep 22	Summerville	0204	33.0	80.2	V	X	X	
	Dec 23	Summerville	0655	33.0	80.2	II	X		
1915	Dec 12	Charleston	1955	32.8	79.8	III-IV	X		
1916	Mar 02	Anderson	0002 (6 shocks)	34.5	82.7	IV-V	X		
	Apr 16	Summerville	0656	33.0	80.2	II	X		
	Apr 30	Summerville	0145	33.0	80.2	II	X		
	Jun 25	Summerville	0705	33.0	80.2	III	X		
	Jul 14	Summerville	1318	33.0	80.2		X		
	Sep 24	Summerville	0442	33.0	80.2	II	X		
1917	Apr 11	Summerville	1401	33.0	80.2	I-II	X		
1920	Aug 01	Summerville	0653	33.0	80.2	II-III	X		
1921	Apr 19	Summerville	1845	33.0	80.2	III	X		
1922	Apr 23	Summerville	1848	33.0	80.2	III	X		
	Aug 08	Summerville	0425	33.0	80.2	II-III	X		
1923	Mar 22	Summerville	2325	33.0	80.2	III	X		
	May 04	Summerville	0555	33.0	80.2	III	X		
	Dec 31	Greenville	2006	34.8	82.5	IV-V	X		
1924	Feb 14	Summerville	1106	33.0	80.2	III	X		
	Jun 03	Summerville	1043	33.0	80.2	III	X		
	Oct 20	Pickens County	0320	35.0	82.6	V (Two moderate shocks felt)	X	X	
1928	Dec 19	Summerville		33.0	80.2		X		
1929	Jan 03	Sumter	0705	33.9	80.3		X		
	Oct 27	Due West	2115	34.3	82.4		X		

* Magnitude indicated as appropriate.

** VPISU - Virginia Polytechnic Institute and State University, 1975.
EHUS - "Earthquake History of the United States, Pub. 41.4, NOAA, 1973.

(1) EHUS - Intensity VI-VII
VPISU - Intensity VII-VIII

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Table 4 **Historic Earthquakes in the General Region of the Richard B. Russell Project Site**

Year	Date	Locality	Time	North Latitude deg	West Longitude deg	Intensity* MM	Source of Data** VPISU	Source of Data** EHUS	Other
			SOUTH CAROLINA (continued)						
1930	Sep 02	Summerville	2030	33.0	80.2		X		
	Dec 09	Due West	1902	34.3	82.4		X		
			(Aftershocks between 03 and 04 hours on Dec 10)						
	Dec 25	Chesterfield County	2224	34.5	80.3		X		
1931	May 06	Due West	0718	34.3	82.4		X	X	
						(This could be Alabama shock of May 5)			
1932	Jan 06	Summerville	0735	33.0	80.2		X		
	Jan 13	Summerville	0740	33.0	80.2		X		
1933	Jul 25	Summerville	2134	33.0	80.2	III	X		
	Dec 19	Summerville	0912	33.0	80.2	IV-V	X	X	
	Dec 23	Summerville	0440	33.0	80.2		X		
			(Aftershock 15 minutes later)						
1934	Dec 09	Summerville	0500	33.0	80.2	IV	X		
1935	Feb 06	Summerville	0736	33.0	80.2		X		
	Oct 20	Summerville	1120	33.0	80.2		X		
1936	Dec 29	Summerville	1401	33.0	80.2		X		
1937	Oct 25	Summerville	1401	33.0	80.2		X		
1938	Aug 04	Charleston	1914	32.8	80.0		X		
1940	Jan 05	Summerville	0845	33.0	80.2		X		
	Oct 07	Summerville	2220	33.0	80.2		X		
	Dec 27	Summerville	0432	33.0	80.2		X		
1942	Oct 31	Winnsboro	2220	34.4	81.1		X		
1943	Dec 28	Summerville	1025	33.0	80.2	IV	X		
1944	Jan 28	Summerville	1330	33.0	80.2		X		
1945	Jan 30	Summerville	1620	33.0	80.2		X		
	May 18	Charleston	0820 & 0840	32.8	80.0	(Blast possibility)	X		
	Jun 05	Wappoo Heights		32.8	80.0		X		
	Jul 26	Columbia	0632	34.3	81.4	V-VI	X	X	
1946	Feb 08	Summerville	1309	33.0	80.2		X		
1947	Nov 01	Summerville	2330	33.0	80.2		X		
1949	Feb 02	Summerville	0552	33.0	80.2		X		
	Jun 27	Summerville	0153	33.0	80.2		X		
1951	Mar 03	Summerville	2155	33.0	80.2		X		
	Mar 07	Summerville	1920	33.0	80.2		X		
	Dec 30	Summerville	0255	33.0	80.2		X		
1952	Sep 27	Summerville	0732	33.0	80.2		X		
						(Felt by one observer)	X		
	Nov 19	Charleston	----	32.8	80.0	V	X	X	
1956	Jan 05	Due West	0300 & 0330	34.3	82.4	IV	X	X	
	May 19	Due West	1400	34.3	82.4	IV	X		
	May 27	Due West	1825	34.3	82.4	IV	X		

* Magnitude indicated as appropriate.

** VPISU - Virginia Polytechnic Institute and State University, 1975.
EHUS - "Earthquake History of the United States, Pub. 414, NOAA, 1973.

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Table 4 **Historic Earthquakes in the General Region of the Richard B. Russell Project Site**

Year	Date	Locality	Time EST	North Latitude deg	West Longitude deg	Intensity* MM	Source of Data** VPISU	EHUS	Other
				SOUTH CAROLINA (continued)					
1958	Oct 20	Anderson	0116	34.5	82.8	V	X	X	
1959	Aug 03	Summerville (near)	0108:30	33	80	VI	X	X	
	Oct 26	McBee (near)	2107:28	34.5	80.2	VI	X	X	
1960	Mar 12	Coast of SC	1247:40	33.0	79	V	X	X	
	Jul 23	Charleston	2237:30	32.8	79.8	V	X	X	
1961	May 20	Summerville	1043	33.0	80.2	III	X		
	Oct 17	Summerville	1935	33.0	80.2	III	X		
1963	Apr 11	Greenville	12:45	34.8	82.3	IV	X		
	May 04	Off Charleston Coast	2101:36	32.2	79.7	IV	X		
1964	Apr 20	Columbia	1303:46.6	34.0	81.0	V	X	X	
1965	Sep 08	Chester	2337:16	34.7	81.3		X		
	Sep 09	Chester	0942:20	34.7	81.3		X		
	Sep 10	Chester	0232:00	34.7	81.3		X		
	Sep 12	Chester	1325:02	34.7	81.3	(N. Central SC)	X		
1967	Oct 23	Orangeburg	0904:10	33.4	80.7	V/3.8	X		
1968	Jul 09	Charleston	2324	32.8	79.8	Felt by one observer	X		
	Jul 10	Charleston	0546	32.8	79.8		X		
	Jul 11	Ashley	2012	32.8	79.7	Felt by two residents	X		
	Sep 22	Batesburg	2141:18.5	34.0	81.5	IV/3.7	X		
						Felt in Richland and Lexington counties			
1969	May 09	West of McCormick	12:14 GMT	33.95	82.58	3.3			Long (1974)
	May 18	West of McCormick	10:54 GMT			3.5			Long (1974)
1971	May 19	Orangeburg	1254:03.4	33.3	80.6	IV/4.1	X		
	Jul 13	Seneca	0642:26.0	34.8	83.0	IV/3.8	X		
	Aug 11	Orangeburg	---	33.4	80.7	3.5	X		
1972	Feb 03	Orangeburg	2311:08.2	33.5	80.4	V/4.5 (aftershocks)	X		
	Aug 13	Central SC	1505			III/3.0	X		
1973	Mar 28	Gaston	0800			2.3-3.0?	X		
	Dec 19	Summerville	1016:08.7	33.0	80.3		X	X	
1974	Aug 02	GA-SC border	0852:09.8	33.9	82.5	VI/4.8	X		
	Nov 22	Charleston	0525:55	32.9	80.0	VI/4.3-4.7	X		EN(1975);EIB
1975	Oct 17	Jocasee Dam	11:31 EST			2.8	X		EIB
1976	Feb 04	Jocasee Dam	19:59 GMT			3.0			Long (1976)

* Magnitude indicated as appropriate.

** VPISU - Virginia Polytechnic Institute and State University, 1975.
EHUS - "Earthquake History of the United States, Pub. 414, NOAA, 1973.

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Figure 13

MODIFIED MERCALLI INTENSITY SCALE OF 1931
(Abridged) (from Barosh')

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, expecially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls made cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbed persons driving motor cars.

IX. Damage considerable in specially designed structures, well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

Figure 13 (Continued)

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Waster spashed (slopped) over banks.

XI. Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

53. The severest historic earthquakes in the seismic zones are as follows:

a. Blue Ridge Zone: Giles County, Virginia, earthquake of 31 May 1897. (The earthquake was in the Blue Ridge physiographic province but not in the mapped region of the Richard B. Russell area.) Epicentral MM intensity is VII (EHUS) and VII-VIII (Bollinger-VPI). Figure 14 shows the felt area of the earthquake. A review of the earthquake has been provided by Bollinger and Hopper (1971).

b. Piedmont Zone. Union County, Carolina, earthquake of 1 January 1913. Epicentral MM intensity is VI to VII (EHUS) and VII-VIII (Bollinger- VPI). A map of isoseismals of the Union County earthquake is provided in Figure 15.

c. Coastal Plain Zone. Wilmington, North Carolina, earthquakes of 18 January 1884 and 5 March 1958. (Outside of Richard B. Russell mapped area.) MM intensity V (EHUS).

d. Charleston-Summerville Zone. Charleston, South Carolina, earthquake of 31 August 1886 had an epicentral MM intensity of IX to X (EHUS). Isoseismals of the Charleston earthquake are shown on Figure 16. Intensity at the Russell site was MM VII. (Adapted from Bollinger, 1976.) See Table 6 for additional treatment of intensity data experienced at the Russell site from the Charleston earthquake of 1886.

Attenuation of Earthquake Motions

54. The attenuation of short-period surface waves in the Piedmont was studied by L. T. Long and is contained in Appendix 1. Long's equation, valid for 20 to 150 km, is:

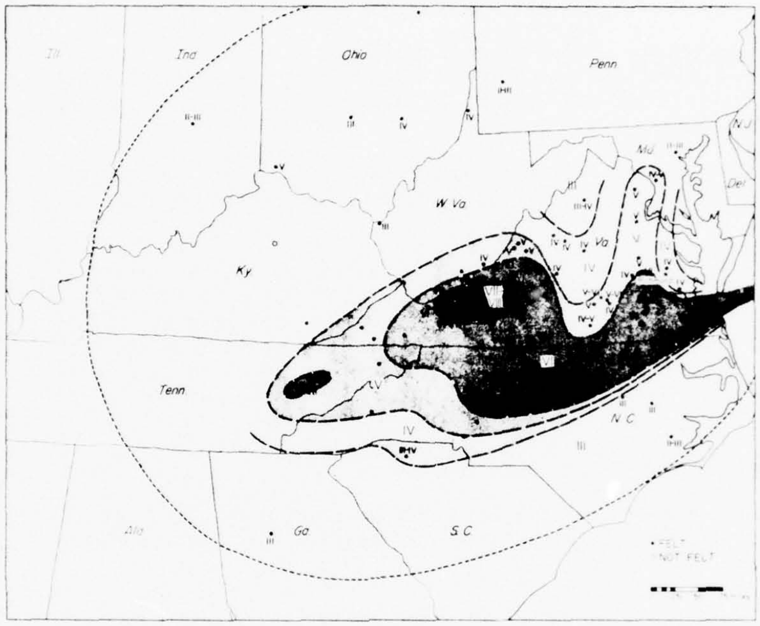
$$\text{Log } (A) = -1.5-2.0 \text{ Log } (D) + M_L$$

where A is velocity in mm/sec; D is km; M_L is Richter magnitude defined at 100 km.

55. An alternative graphical solution, developed for this report by E. L. Krinitzsky and Frank K. Chang, is presented in Figure 17. The graphs were developed from seven earthquakes in central and southeastern United States. Distance from source, in kilometers, is related to change in MM intensity for medium to very large earthquakes. M_b (magnitude of body wave) is from 4.7 to 7.2 and M (general Richter magnitude) is 5.5 to 7.5.

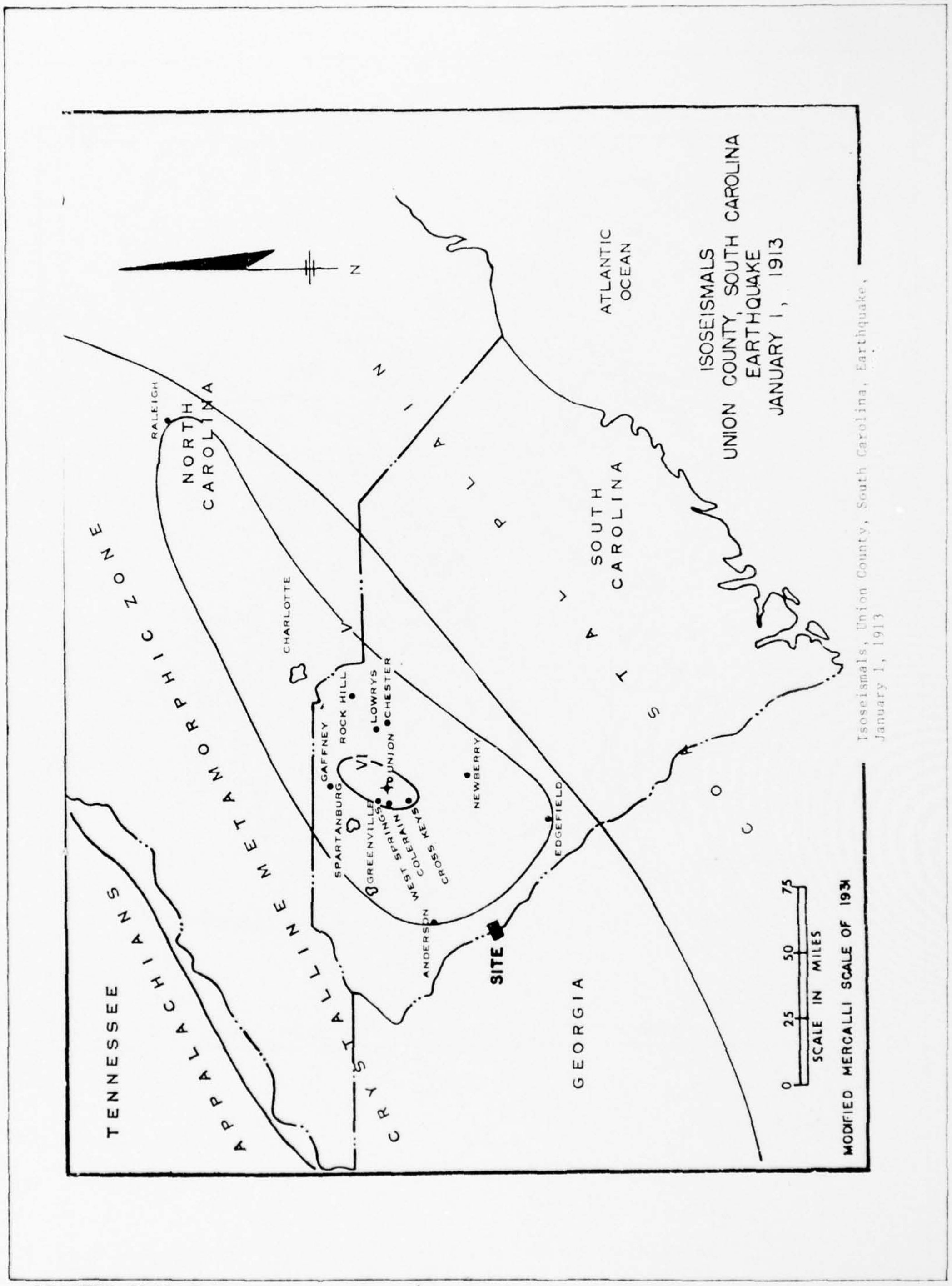
Historic Earthquakes at the Richard B. Russell Damsite

56. Historic earthquakes felt at the Richard B. Russell Site are tabulated in Table 5. Intensities of earthquakes that affected the region during historic time were interpreted for their intensities at the Richard B. Russell Damsite. The severest motions at the site were



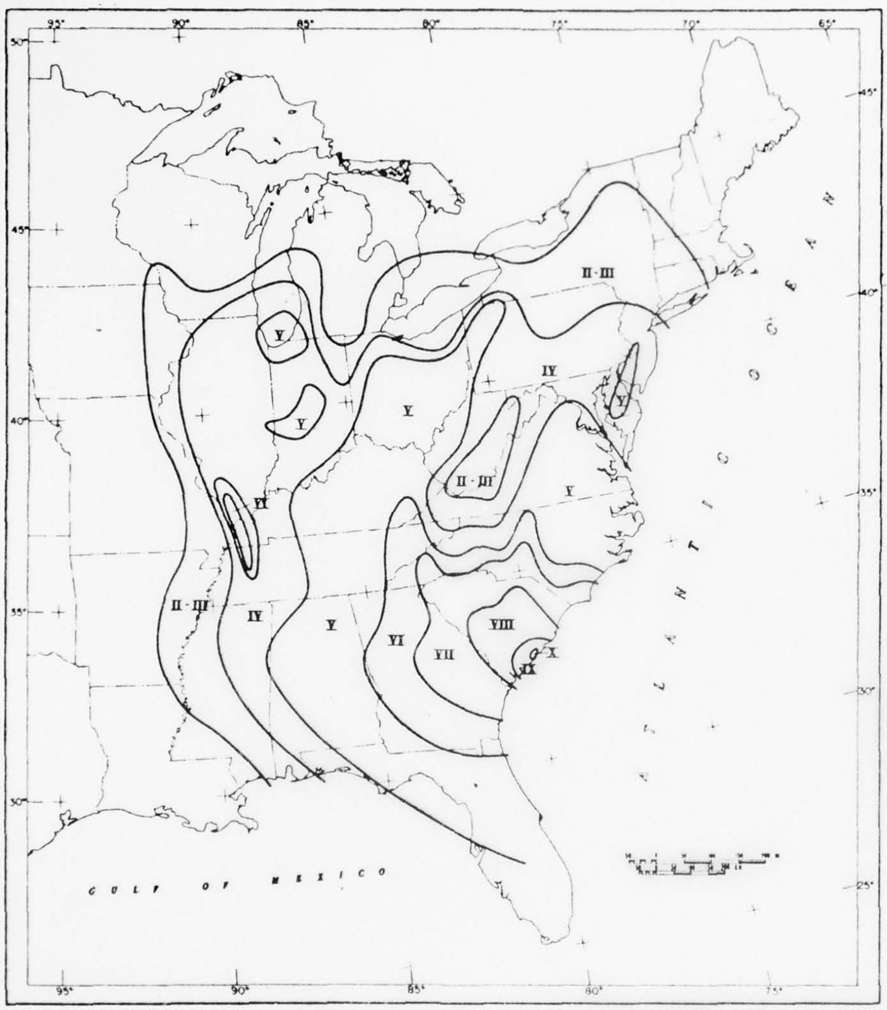
Isoseismal Map for the Giles County, Virginia, Earthquake of May 31, 1897. From Bollinger and Hopper (1971)

FIGURE 14



ADAPTED FROM THE STUDY BY LAW ENGINEERING FOR THE CATAWBA NUCLEAR POWER STATION.

FIGURE 15



Isoseismal Map for the 1886 Charleston, SC Earthquake. Contoured to show the Broad Regional Pattern of the Reported Intensities (Bollinger, 1976).

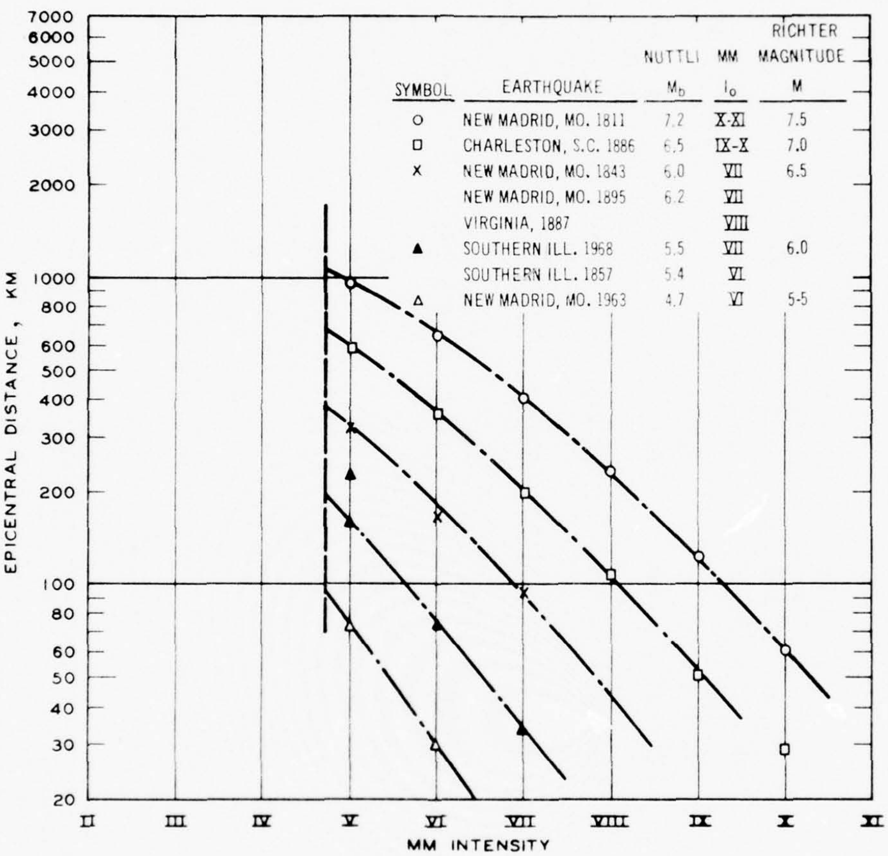
FIGURE 16

Table 5 Historic Earthquakes Felt at Site of Richard B. Russell

Earthquake	Date	Epicentral Distance (KM)	Epicentral Intensity (MM)	Interpreted Site Intensity (MM)	Source of Isoseismal Map	Seismo-Tectonic Region
New Madrid MO	12/16/1811 1/23/1812 2/07/1812	850	XI X-XI XI-XII	VI	Nuttli (1973b)	New Madrid
Charleston SC	8/31/1886	300	IX-X	VI	Nuttli (1974)	Charleston-Summerville
Giles County VA	5/31/1897	440	VII-VIII	III	Bollinger-Hopper (1971)	Blue Ridge
Union County* SC	1/01/1913	110	VI-VII	IV-V	USGS-NEIS and Law Eng. Testing Co. (1972)	Piedmont
Hartsville SC	10/26/1959	190	VI	not felt	USGS-NEIS	Coastal Plain
NC	5/13/1957	200	VI	III	USGS-NEIS	Piedmont
E. TN	11/30/1973	240	VI	III	USGS-NEIS	
Charleston SC	11/22/1974	300	VI	III	Benson, et al (1975)	Charleston-Summerville
McCormick GA & SC border	8/02/1974	15	V	IV	Benson & Fogle (1974)	Piedmont
Lincolnton GA	11/01/1875	25	VI	V	Rockwood (1876) & Denman (1974)	Piedmont
Lake Murray SC	7/26/1945	100-120	VI	III	---	Piedmont

USGS-NEIS: U. S. Geological Survey-National Earthquake Information Service.

* The Union County earthquake of 1 January 1913 has been re-studied by the Law Engineering Testing Co. for the Catawba Nuclear Station, Duke Power Company. Their study indicates that the maximum epicentral intensity observed from this earthquake was nearly MM VII, opposed to the reported intensity of a high VII or low VIII MM.



Relation of MM Intensity to Epicentral Distance in Central and Eastern United States (Krinitzsky and Chang).

FIGURE 17

Intensity VI for the New Madrid (1811-1812) and VII for the Charleston (1886) earthquakes. The Union County, South Carolina, earthquake of 1 January 1913 was MM IV to V at the Russell Site. The Willington* earthquake (1974) that occurred near the Clark Hill Lake was felt as a MM IV to V. Thus, the worst historic earthquake shaking at the Richard B. Russell Site was MM VII, which represents the Charleston 1886 great earthquake. Only considerable damage in poorly built or badly designed structures occurred. Damage from the 1886 Charleston earthquake is described by Baker (1933).

*This earthquake occurred near the small town of Willington, South Carolina, and is variously known as the "Clark Hill Reservoir Area" or "McCormick County" earthquake of 2 August 1974. Two separate isoseismals have been published by Talwani and Schleffer (1976) and Long (1974).

PART VI - EXAMINATION FOR ACTIVE FAULTS

57. Earlier sections of this report have established that mapped faults are ancient ones which date back to orogenies during middle Paleozoic time and to subsequent disturbances during Triassic and Tertiary time. The predominating lithologies of metamorphosed volcanics and sediments do not readily show faults due to thick saprolite and vegetative cover. Thus, faults are difficult to recognize in the field, even though strong geophysical evidence indicates their presence. Most of the faults investigated in close proximity to the project were exposed because of secondary consideration, i.e., location of the diversional channel, the presence of an earthquake in the vicinity, economic interest, and so forth.

Association of Earthquakes with Tectonism and Faults.

58. Earthquakes are associated with faults on the basis of elastic rebound theory. Strains build up in the rocks due to tectonism and exceed rock strength. The rock fails by slipping along a fault, and the strain is relieved along the plane of the fault. Thus, the strained portions of the rock can experience a sudden rebound. The movement occurs elastically, and vibratory motions (the earthquake) are set up.

59. The tectonism which developed the faults in the project area occurred early in geologic time. Considerable erosion has taken place since then, but there has been no tectonism during the intervening time and none is evident at present. Isostatic rebound is occurring. Its contribution toward the activation of faults is believed to be minor; however, many of the small earthquakes, Intensity V or less, might be attributed to isostatic rebound.

60. From the evidence provided by historic earthquakes, present-day tectonism appears to be geographically restricted to an irregular belt along the coast and shelf area. This tectonism is poorly understood, but the major earthquakes at Charleston are presumed to be the result of fault movements along this zone of activity. The historic earthquakes have not caused fault movements that are seen on the ground surface. Such movement has occurred presumably in the subsurface.

Definition of Active Faults.

61. Faults are considered to be active if it is judged that they may move at some time in the near future. For engineering, it means that they have the potential for moving during the life of a structure. The principal criterion for making this prediction is whether they have moved in the recent past.

62. The Nuclear Regulatory Commission (formerly the Atomic Energy Commission) uses the following criteria (1971, 1973):

a. Datable movement during the past 35,000 years.

b. Datable movement more than once in the past 500,000 years.

c. Structural interrelation whereby a fault can be shown to move if movement occurs on a different fault with proven activity.

d. Instrumentally determined macroseismic activity relatable to a fault.

e. Projection of a proven active fault through or into areas where all evidence of the fault or its activity is obscurred, as by thick alluvium.

63. The International Atomic Energy Agency (1972) adds the following criteria:

a. Evidence of creep movement along a fault. Creep is slow displacement, not necessarily accompanied by macroearthquakes.

b. Topographic evidence of surface rupture, surface warping, or offset of geomorphic features.

64. It is common in engineering evaluations to call a fault active if it disturbs any Holocene deposits (no older than 10,000 years). Displacement of surficial gravels, recent swamp deposits, and Holocene alluvium are accepted criteria. (The latter includes displacement of A and B horizons of soil, palesol, saprolite-soil interface, and other surface markers.)

65. All of the above criteria depend on surface manifestations of fault movements. Faults may move in the subsurface and have no surface manifestations. A lack of surface evidence is common east of the Rocky Mountains in the United States and in Canada.

Mapped Faults.

66. Detailed studies and traverses were made across mapped faults and lineations in order to examine the faults for evidences of movement (Appendix D contains studies). No evidence of movement was seen.

67. Local residents were questioned to learn if they knew of ground breakage anywhere in the area. No one knew of any such events.

Linears and Lineaments.*

68. It is generally recognized that most earthquakes of large magnitude disrupt the ground surface locally. Since this disruption will often be localized along an existing fault and will be followed by other movements along adjacent portions of the same fault, a more or less continuous narrow zone of surface disruption develops over geological time. These surface features provide excellent clues to the seismic activity of a region. Long, continuous, narrow zones indicate a high degree of seismic activity at the present time, while the lack of such zones may strongly suggest aseismic conditions.

69. Accordingly, a thorough study of the ground surface in the Piedmont Province and adjacent provinces was undertaken as a part of the study for the Richard B. Russell Project. Inspection of aerial photograph mosaics had revealed that the surface conditions were not well exposed for the direct visual approach, and similarly, the imagery from satellites showed little potential for the details sought here. Instead, it was felt that a detailed examination of topographic maps would prove most effective.

70. All available current topographic maps were examined in the region of interest. These raw data were particularly useful in that they eliminate the necessity for considerable subjectivity such as used in the interpretation of aerial photographs. Factors such as sun angle, season of the year, agricultural and cultural overprints, and photographic quality and technique were completely removed. The remaining subjectivity arose in judging whether features evident in the topography are actually related to geology and tectonic history or, instead, are strictly geomorphic.

71. Topographic map coverage for the region is complete. In only a few places is there a lack of 7-1/2-minute quadrangle coverage, and at these places, 15-minute quadrangles are available. The contour intervals are either 10 or 20 feet so that even the gentle topography of the Piedmont Province is adequately revealed.

72. Over 175 topographic maps were examined in detail for this study. Features or combinations of topographic features that appeared to have a linear nature extending over a distance of at least a few miles were located and retraced on a base map of the AMS series of topographic

*Linears, as intended in this study, are straight features of topography extending usually for a few miles. Lineaments are long linears or combinations of linears. The reader may find a recent review of terminology useful (O'leary, et al, 1976).

maps covering one- by two-degree areas. Portions of this series provide complete coverage for the area of interest. Lineaments mapped in this manner had lengths averaging approximately four miles, as seen in Figure 18. Typical features represented by linears on the map are:

a. Alignments of round knolls.
b. Alignments of broad saddles.
c. Straight portions of stream valleys.
d. Long straight embayments from lakes.

73. In the course of assembly of the data, it was found that the style of topographic linears consists of two types of patterns evident throughout, at least locally. However, the development of linears was noticeably poorer in the onlapping younger formations in the southeastern portion of the region, i.e., the Coastal Plain Province. The flat-lying, softer formations in this province apparently were not conducive to the development of linears. In fact, some of those features shown on Figure 18 are probably geomorphic rather than structure related.

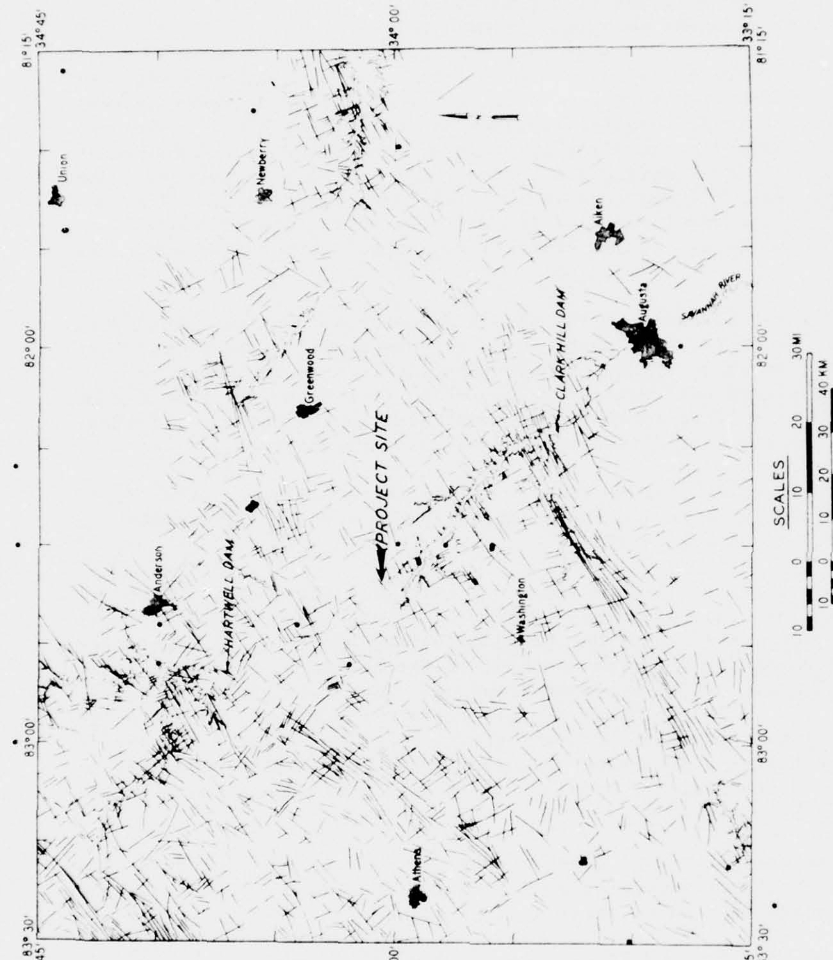
74. Within and adjacent to the Blue Ridge Province in the northwest corner of the region, the development of topographic linears improves, and not all of those evident on the topographic maps are shown on the figure. The more systematic development in this part of the region appears to be related to the more common occurrence there of folded, layered formations of different hardness and erodability.

75. The Brevard Fault zone (Figure 19) at the northwest of the Piedmont Province is expressed topographically by several lineaments in the upper left of Figure 18.

76. Two patterns of linears stand out in Figure 18. First, there is apparently an evenly dispersed pattern of linears that seem to fall in two or more sets around any given locality. Usually, the two sets are oriented at right angles and conform for the most part with the structural grain of the Piedmont Province. One set trends approximately N 35°W while the other overall prefers a trend of about N 55°E. It is concluded from the present study that the evenly dispersed linears represent a pervasive structural grain manifested by differential erosion along dikes, bedding, and schistosity and by enlargement of joints (Figure 9).

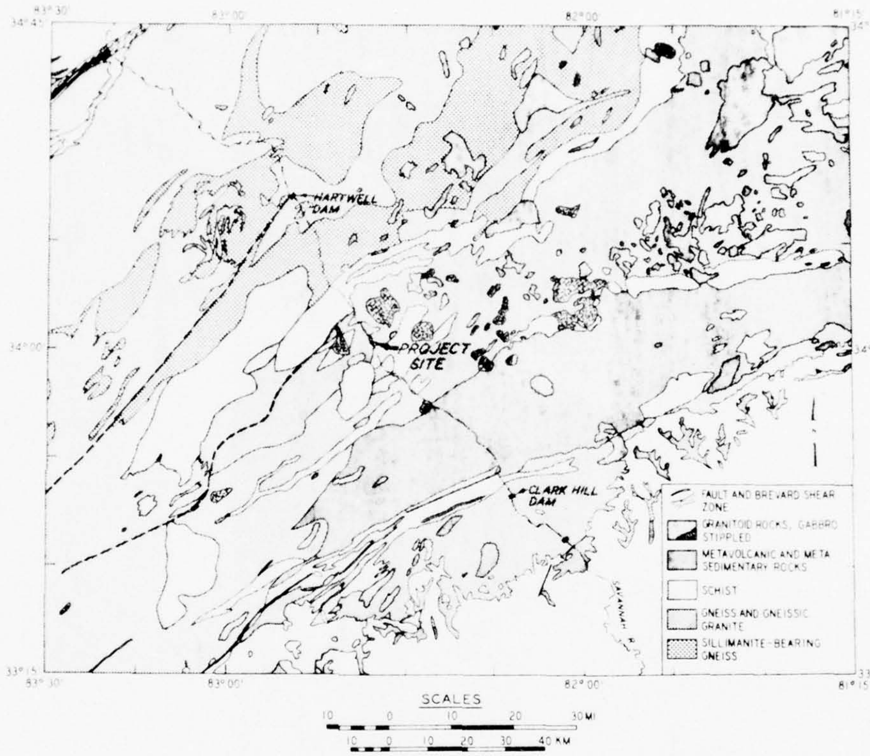
77. The second pattern of linears consists of narrow, concentrated zones of lineaments extending considerable distances. These narrow zones coincide with known shear ancient zones.

78. Figures 20, 21, and 22 show the lack of sharp expression in aerial photographic mosaics of two old fault zones and the Belair fault. Figure 21 shows the Lowndesville belt which exhibits the best lineament expression in aerial photographs within the entire region,



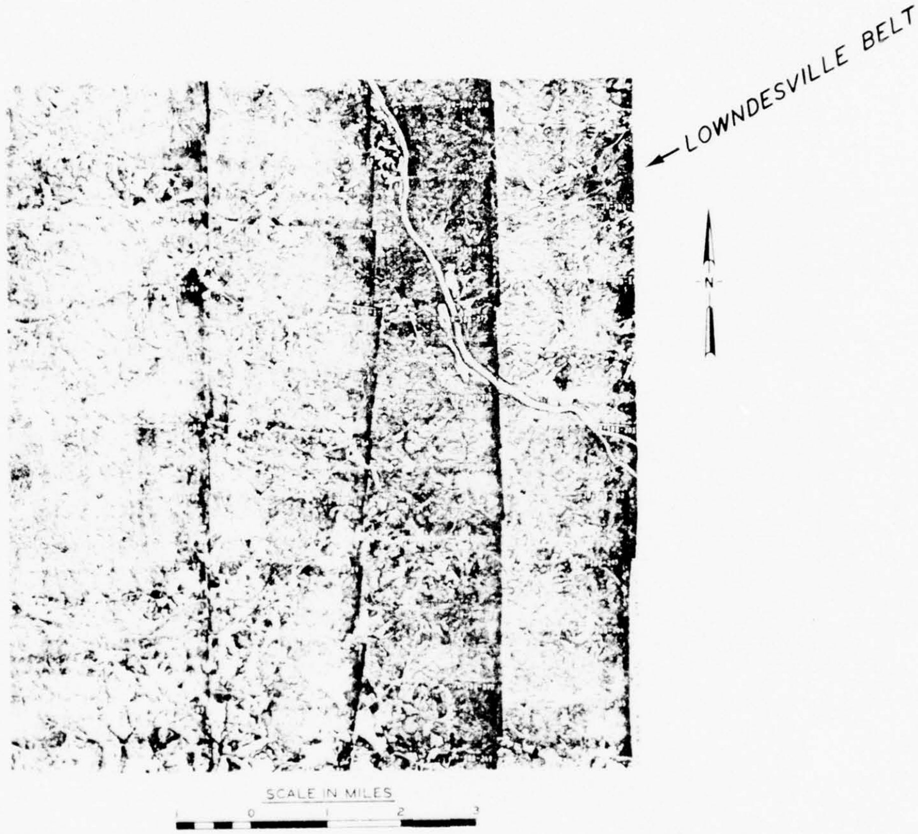
Topographic Lineaments - Richard B. Russell Project

FIGURE 18



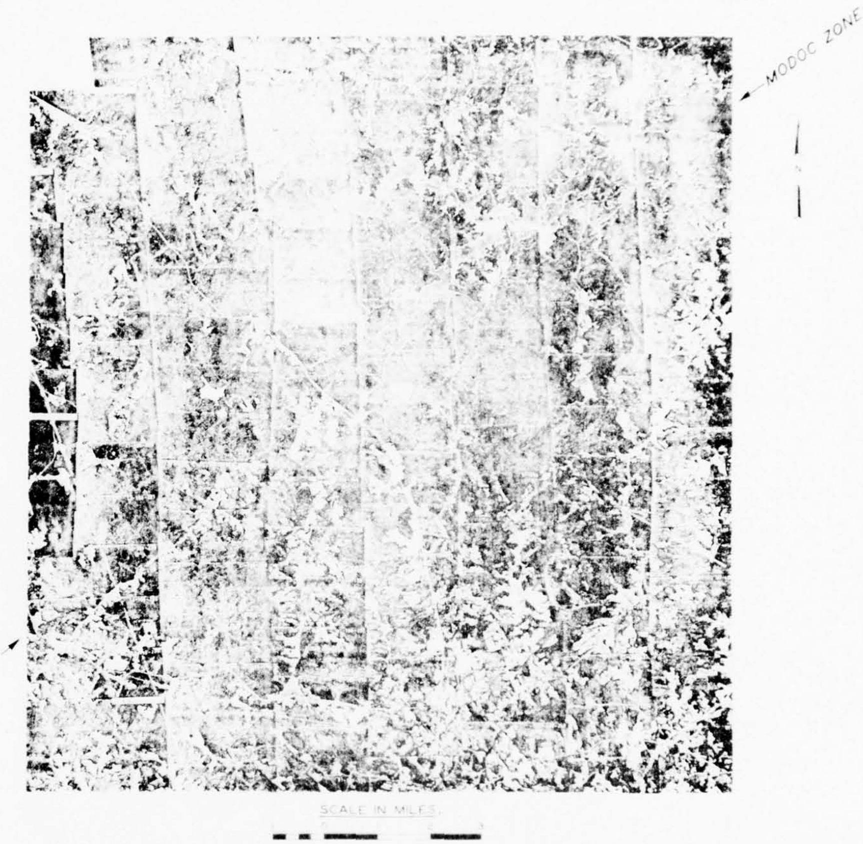
Geology of Region around Richard B. Russell Project Site

FIGURE 19



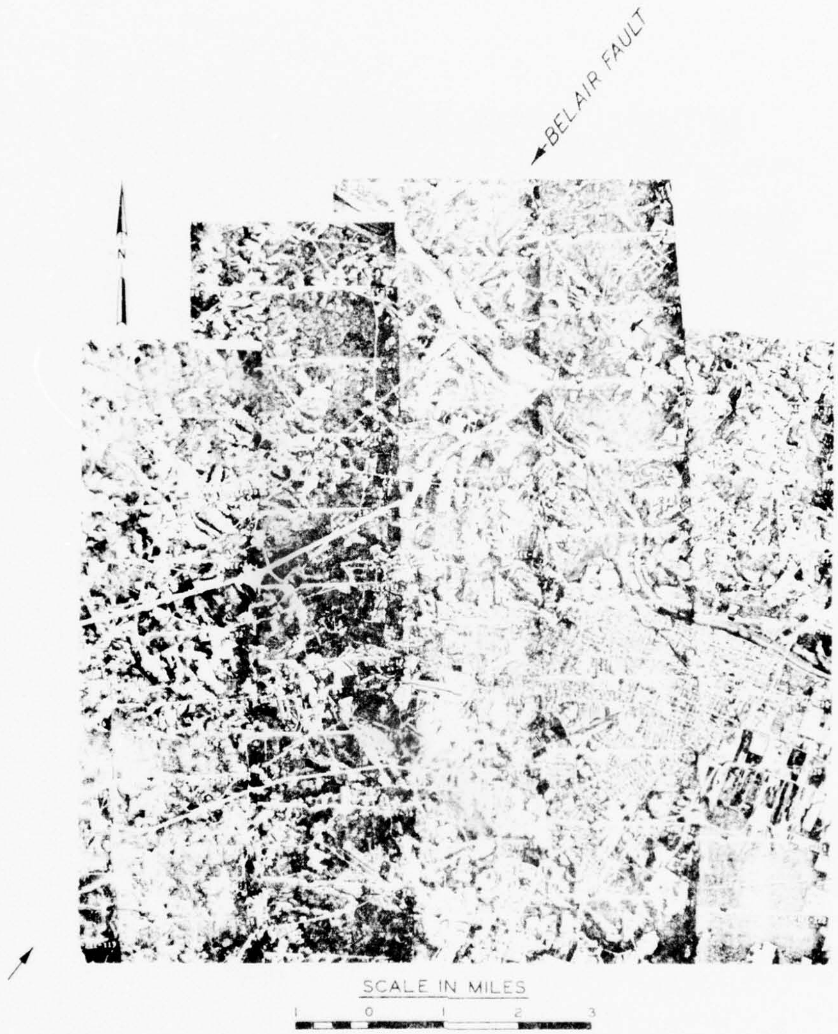
Aerial Photographic Mosaic Showing Lowndesville Belt
Southwestward to Savannah River.

FIGURE 20



Aerial Photographic Mosaic of Modoc Zone in Little River Arm of Clark Hill Reservoir.

FIGURE 21



Position of Belair Fault Northwest of Augusta, Georgia.

FIGURE 22

with the possible exception of the Brevard Fault zone. The Lowndesville belt appears as linear features on a trend S 60°W to the Savannah River. Continuation of this belt southwestward into Georgia is not evident in the aerial photographs. Figure 21 indicates the position of the Modoc zone in the Little River arm of Clark Hill Lake. Southwest from the reservoir, very little indication of this zone is found in the aerial photographs.

79. Figure 22 shows the position of the Belair fault on the outskirts of Augusta, Georgia. The fault has been mapped from its northeast extremity at the Savannah River in the upper part of the mosaic to its southwestern extremity near the edge of the figure. No evidence of this fault can be found in the aerial photographs, and systematic examination of topographic maps (Figure 18) indicated no topographic expression.

80. The distribution of earthquakes and general seismicity of the region are summarized in Figure 12. Felt earthquakes for portions of Georgia and South Carolina are summarized in Table 4 (5 sheets).

81. The geographical distribution of earthquake epicenters in the Piedmont Province shows no obvious correlation with the pattern of linears. This is an additional confirmation of the suggestion above that linears and lineaments are related to geological grain rather than ground breakage from earthquake activity.

82. Throughout that portion of the Blue Ridge Province that falls in the region of interest, no correlation of epicentral location and lineament pattern has been found. Epicenters appear to be distributed more or less randomly in this province.

83. The distribution and fault mechanism deduced by Talwani (1976) for microseismic activity following the August 1974 earthquake suggest an active surface striking parallel to the structural grain.

84. Topography at this locality was carefully examined but revealed no surface expression. Linear topography or even surface scarps might be expected to be associated with long continued activity along a fault.

85. It is concluded from the study of topography that the evenly dispersed linear pattern represents a pervasive structural grain manifested by differential erosion along dikes, bedding, and schistosity and by enlargement of joints. On the other hand, the narrow zones of linears and lineaments seem to be associated with known shear zones of ancient age. No lineaments were found in this systematic study that resemble those along presently active fault zones in other regions of the world. No surface features were found in the region to support recent fault activity such as has been suggested for the Belair fault and the Patterson Branch fault.

Activity of Faults.

86. Faults near the site show no evidence of any recent activity. Included below is the summation of specific investigations which sought evidence of recent fault activity.

Modoc Fault.

87. The Modoc fault was examined in detail along the shores of Clark Hill Lake and along South Carolina Highway 28 and Georgia Highways 47 and 78.

88. No direct evidence was found indicating recent movement. Mylonitic rocks and highly cataclastic gneiss, "button schist" and flow-folded amphibolite within the zone have undergone a period of penetrative deformation and rapid increase in metamorphic gradient. Bedding thrusts were found and traced short distances, as were minor offsets of strike-slip type along the north trending joint system. All shear features, offset joints, and thrusts indicated movement restricted to the remote geologic past. No evidence of movement in the past 10,000 years was found in this study. Details of this study is contained in Appendix 3.

Faults in the Western Portions of the Proposed Lake Impoundment.

89. The study of this area found no evidence of active faulting. The scope of the study is felt to be adequate when viewed in the light of the intensive investigations of other South Carolina investigators. The Lowndesvile belt, like the Modoc Zone, indicated no recent movement. Details of this study is contained in Appendix 3.

Diversion Channel Fault.

90. This fault exposed in the diversion channel has been dated from 365 M.Y.B.P. to 270 M.Y.B.P. A stress history analysis, including radiometric dating, was performed by Dr. James Neiheisal, South Atlantic Division Lab, and this report is included in Appendix 3.

Patterson Branch Fault.

91. The existence of the Patterson Branch fault was first indicated by detailed mapping conducted in connection with aftershock studies of the 2 August 1974 earthquake at Willington. Since this fault was oriented parallel to one possible fault plane solution for the shock, it was further studied geologically. No movement was found to have recently occurred along this fault. An independent evaluation of this fault by Dr. Donald Secor, University of South Carolina, is included in Appendix 3.

Towaliga Fault, Projection in Elbert and Hart Counties, Georgia.

92. The Geologic Map of Georgia (1976) shows the Towaliga Fault to possibly splay into two branches, one intersecting upstream from the proposed Richard B. Russell Dam and the other intersecting upstream from the existing Hartwell Dam. Detailed examination utilizing field mapping and geophysical techniques failed to reveal evidence for the location of the fault as it is placed on the maps. Shear zones and FCR breccia dikes occur in the area. No evidence of recent movement was found along these zones.

Belair Fault.

93. The Belair Fault was investigated by the Corps of Engineers and the USGS. The Corps investigated that section in Fort Gordon military base while the USGS investigated the portion of the fault extending through Richmond and Columbia Counties, Georgia. In November 1976, the USGS announced that the final results of their investigation indicated that movement has not taken place within the last 2,500 years, although movement had occurred within the last 50 million years. Details of this study is contained in Appendix 3.

PART VII - INTERPRETED MAXIMUM EARTHQUAKE GROUND MOTIONS AT THE DAMSITE

94. Historic seismicity was used as the basis for interpreting the maximum events that could be expected at the damsite.

Seismic Risk Zones and Maximum Earthquakes.

95. Seismic Risk Zones, from which earthquake events can be expected to be registered at the Richard B. Russell site, are listed in Table 6. These zones are the Blue Ridge, Piedmont, Coastal Plain, Charleston-Summerville and New Madrid (southeastern Missouri and adjacent areas). Maximum historic intensities are given for each zone.

96. The maximum historic intensity was taken as the basis for the maximum earthquake that will occur. The historic record for large events is on the order of 200 years. The inclusive areas that have been considered, the entire Atlantic Coastal Plain for example, are very large. The large area should compensate for the relatively short record in any one place. The concept of reviewing a large area can be extended still further. East of the Rocky Mountains, there are only a few areas of strong earthquake activity. These are New Madrid, the St. Lawrence Valley, and Charleston. Without these active centers in which severe earthquakes have occurred, the maximum intensity of earthquake for the region east of the Rock Mountains is VII with a corresponding order of magnitude* (M) of 5.5 (Nuttli, 1976, personal communication). An intensity of VII to VIII is postulated by Bollinger for the Union County, South Carolina, earthquake of 1 January 1913; however, VII is taken to be the value of the Law Engineering (1972) and VI to VII is given by the EHUS (Coffman and van Hake, 1973). Though an VIII may be interpreted because of some local susceptibility, a strong VII appears to be the most likely maximum intensity for earthquake effects in this region. For the Coastal Plain, the intensity is V to VI and is closer to M of 5.

97. In the zones of very strong seismicity, Charleston-Summerville and New Madrid, again the maximum earthquakes are interpreted to be equal to the maximum historic events. The New Madrid earthquakes of 1811-1812 are comparable to the largest that have occurred in North America excluding the Alaska earthquake of 1964. The New Madrid area clearly does not have a comparable potential in magnitude, but the

*Magnitude (Richter scale) is calculated from a standard earthquake, one which provides a maximum trace amplitude of one micrometer on a Wood- Anderson torsion seismograph at a distance of 100 km. Magnitude is the log of the ratio of the amplitude of any earthquake at the standard distance to that of the standard earthquake. Each full numeral step in the scale (2 to 3, for example) represents an energy increase of about 32 times.

historic intensity of XI for New Madrid was not exceeded in the Alaska earthquake. For the Charleston-Summerville area, a maximum intensity of X is assumed on the basis of the 1886 event.

98. In none of these seismic risk zones is it possible to restrict the maximum earthquakes to identifiable faults. Thus, the assumption must be made that the earthquakes can occur anywhere in their respective zones.

99. In the Piedmont, the maximum earthquake, with an intensity of VII and a corresponding magnitude of 5.5, can occur at the site. (This premise is based upon the most severe historic seismicity and the work of Long (1976), bound in Appendix 1). Thus, in Table 6, a zero distance is shown. The focal depth is taken to be 5 to 10 km. The faulting is reverse, or thrust, since the rocks are in compression (cf Sbar and Sykes, 1973). Table 6 is on page 61.

100. Table 6 shows distance in km to the nearest boundaries of the Blue Ridge, Coastal Plain, Charleston-Summerville, and New Madrid zones. Maximum earthquakes for each of these zones have been attenuated to the Richard B. Russell site, and site intensities are given. These values represent the worst earthquake effects that can be expected at the Russell site from the specified seismic risk zones.

The Problem of Reservoir-Related Earthquakes.

101. About 30 reservoirs over the world have experienced seismicity which may, in some cases, be related to reservoir loading and in other cases be unrelated. Many hundreds of reservoirs have experienced no seismicity.

102. A concern at the Russell site is the question of possible induced seismicity. A connection has been made between the presence of dams and earthquakes. USGS, Branch of Earthquake Mechanism in Washington, DC, is critical of reports that link damsites and earthquakes by statistical inference. Dr. James Devine, USGS geophysicist, contends that these reports fail to take into account background seismicity, or quakes that would occur regardless of dams being built. Devine stated that the places you build dams are also places where there are often earthquakes (San Francisco Examiner, January 1977).

103. A tabulation of 300 reservoirs around the world with heights of over 100 meters show the following: Two hundred and sixty-eight show no change in seismicity; twenty have shown increase in seismicity of which five have had destructive earthquakes.

104. The record for Piedmont Province reservoirs is as follows: Fifty-nine reservoirs exist in the Appalachians; ten of the fifty-nine have had minor earthquake(s) after impoundment; one of the ten, Clark Hill, has had two felt earthquakes. One occurred in 1960 at a distance from the dam which would preclude induction; the other, at

Willington, South Carolina, 1974, is discussed in Paragraph 106. The ten reservoirs can be further subdivided to show that six of the ten did not experience the earthquake until seven years or more after impoundment, and four of the ten did not experience the earthquake until four years after impoundment. Since reservoir-induced earthquakes appear to occur upon reservoir filling and for five to ten years afterwards, but are not known to have occurred 10 to 20 years after impoundment, the record for Piedmont Province reservoirs indicates that they have not shown induced seismicity; rather, they only reflect the natural seismicity of the region.

Earthquakes at Clark Hill Reservoir.

105. Two felt earthquakes have occurred nearby in the Clark Hill area. One was the MM Intensity VI earthquake at Lincolnton, Georgia, on 1 November 1875, about 25 km from the Russell site. The other was the Willington, Georgia-South Carolina, earthquake, Intensity V, of 2 August 1974, which was about 15 km from the Russell site.

106. The first earthquake, in 1875, occurred long before there was a reservoir on the Savannah River. The second, in 1974, occurred in the environs of the Clark Hill Lake; however, Clark Hill had been in operation then for 21 years. The long period of time between filling of the reservoir and the occurrence of the 1974 earthquake indicates that the earthquake is independent of the reservoir.

Microearthquakes at Clark Hill Lake.

107. The 1974 earthquake was followed by a series of aftershocks in the form of microearthquakes (events so small that they are felt only by instruments). These microearthquakes were observed intermittantly by Talwani (1976) during a 7-1/2-month period after the earthquake. The reservoir level had a rise of five feet in three days during a period when observations were being made. Talwani noticed a corresponding increase in seismic activity with a 2-day lag. This short period of observation is insufficient to demonstrate a conclusive relationship between the small reservoir rise of five feet in three days and the increase in microearthquake activity. Further observations are desirable and are being made to establish background levels of local microseismicity.

108. The microearthquakes have occurred in an elliptical zone which trends northeast to southwest. The major axis is about five km in length, and the minor axis is about two km according to Bridges (1975). The microearthquakes are shallow. They are most numerous at from the near surface, one-half to one km, to about five km (Long, 17 December 1976). They diminish in number with depth and die out at about 20 km. The zone forms a seismic hotspot. Its location is roughly along a boundary between two zones of metamorphic rocks, the Carolina slate belt and the Charlotte belt. Composite fault plane solutions of aftershocks show that the movements are strike slip and dip slip (see Scheffler, 1973).

109. Compressional and tensional forces may work together in this portion of the Piedmont. One can visualize a situation, akin to that of a glacier, where there is flow at depth through a process of plastic deformation in which the forces are compressional. Near the surface, the glacier is shattered with fissures and crevasses representing conditions of tension. The contrast is there because motion is not uniform through the section. Similarly, lateral motions in zones of rocks in the Piedmont may be taken up by a sort of plastic flow. Adjacent rocks with dissimilar properties of deformation may not deform in concert. The nondeforming material may then behave as a brittle substance and shatter, producing microearthquakes within a narrow, shallow zone akin to the crevasse areas of a glacier. At depth, the rock may deform plastically and not be active seismically.

110. A model, similar to that described above, would explain the hotspot of seismicity at Clark Hill. It would explain the shallow, isolated character of the hotspot and the absence of hotspots at other areas, notably at the nearby Hartwell Lake.

111. If the above concept of a hotspot is valid, the model is self-limiting with regard to the maximum earthquake that can be generated in a hotspot. The dispersal of movement along a zone of shallow faults presupposes a dispersal of the energy available for earthquakes; therefore, there will not be a buildup to a very large earthquake.

Calculation of Maximum Induced Seismicity.

112. Appendix 1 contains a theoretical analysis prepared by Dr. L. T. Long for defining the maximum value for a possible induced earthquake in the Piedmont area of the Clark Hill and Russell Lakes. Long places limits that define a maximum earthquake by limiting the size of activity on a fault plane to 39.5 km^2 in accord with the extent of microearthquake activity observed near Jocassee Lake. Microearthquakes at Clark Hll indicate a fault plane of about 10 km^2. The stress drop estimates for these events is six bars. For this combination of six bars and 39.5 km^2 of activated fault, a maximum magnitude of 5.6 is calculated. The value is consistent with the maximum magnitude of 5.5 previously cited from seismic history.

Evaluation of Possible Induced Seismicity.

113. Though a maximum induced earthquake can be postulated, equal to the maximum seen in the historic seismicity over comparable portions of eastern United States, there is no reliable and proven method in the present state-of-the-art by which to say that an induced earthquake will or will not occur (cf report on induced seismicity by Dr. David T. Snow in Appendix 1 and critique by Don C. Banks, Frank McLean and E. L. Kinitzsky). The most conservative analysis is to assume that an induced earthquake will occur and that it will occur at the damsite. Table 6 lists two earthquakes at the damsite. One is

for a reverse fault in accord with the regional tectonics. The other is a tensional fault. The tensional fault is in accord with the interpretation from aftershocks in the Clark Hill area. Both events are magnitude 5.5, MM Intensity VII, and with focal depths of 5 to 15 km for the thrust fault and 1 to 10 km for the normal fault. Maximum Earthquake, occurring at the damsite with two possible focal plane and fault mechanisms, is adopted as a Design Earthquake. Therefore, bedrock ground motions scaled from selected earthquake records representative of the design earthquake will be accommodated for and utilized under the dynamic analysis.

114. Snow, when writing about induced earthquakes (cf Conclusions, page 50 of Appendix 1), states that "there is scant evidence (except Koyna) that the maximum probable quake may exceed the expectation of natural events... ." Were the Koyna area to have been studied in the same way as Richard B. Russell, the active surface faults at Koyna would have been recognized and a set of motions much more severe than those felt at Koyna would have been assigned.* In fact, with a much less hazard, the Richard B. Russell site was given motions that are as severe as those experienced by the Koyna earthquake of Magnitude 6.5. Table 10 lists the Koyna earthquake with a scaling factor of one for use at the Richard B. Russell Site.

Near Field Versus Far Field.

115. Table 6 shows peak motions that were assigned for near and far field conditions.

116. Near and far field values for MM intensity versus horizontal acceleration are shown in Figure 23. The data are those of the 187 strong motion records from western United States that were uniformly processed at the California Institute of Technology. Peak values in the far field are a fifth of those in the near field for corresponding MM intensities. The records were selected because of availability and a noted lack of appropriate strong motion records for eastern United States.

117. In the near field, complicated reflection and refraction of waves occur in the subsurface with resonance effects and a large range in the scale of ground motions. Intense ground motions and high-frequency components of motion are present. In the far field, the wave patterns are orderly; the oscillations in wave forms are more muted and more predictable; and frequencies are lower.

*Gupta, et al (1969), notes that seismicity at Koyna was noted prior to impoundment, and rare tremors were observed by inhabitants near the construction site. The seismograph operating at Poonna (distance from the site 120 km) also reveals tremors for this region prior to the dam being built.

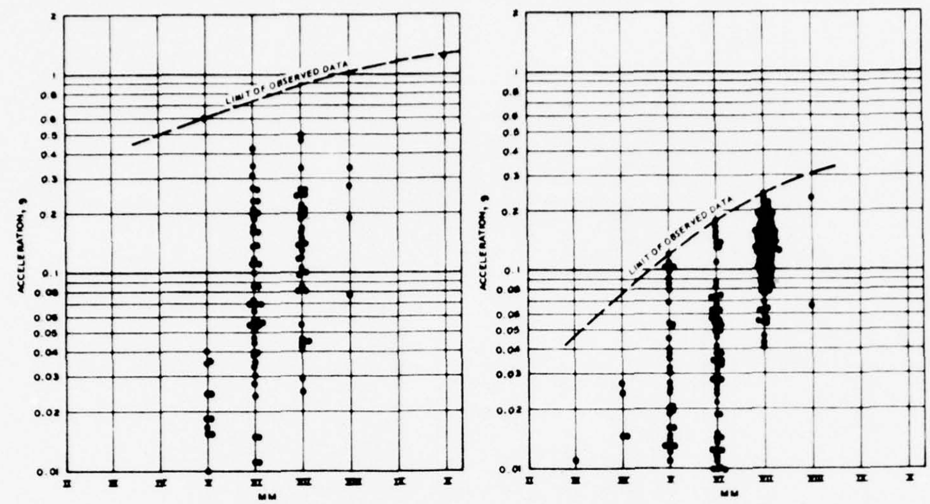
Table 6 Interpreted Peak Ground Motions at the Richard B. Russell Site

Seismic Risk Zone	Max Historic Intensity MM	Intensity at site MM	Max Mag M	Distance km	Focal Depth km	Field	Fault Type	Richard B. Russell Site Peak Motions** Accel. g	Vel. cm/sec	Displ. cm	Bedrock Duration sec
Blue Ridge	VII	V	5.5	100	15	Far	Reverse	0.12	15	10	9
Piedmont	VII	VII	5.5	0	5-15	Near	Reverse	0.4-0.5	30-45	20	5
		VII	5.5	0	1-10	Near	Normal*	0.4-0.5	30-45	20	5
Coastal Plain	V-VI	IV	5.0	100	10	Far	Reverse	--	---	-	---
Charleston - Summerville	IX-X	VI ***	7.0	250	15	Far	---	0.18	20	12	10
New Madrid	XI	VI	7.5	680	15	Far	---	0.18	20	12	10

* Normal: Normal fault for reservoir-induced earthquake.

** Note: Operating basis earthquakes for design of concrete structures may use one-half the peak motions.

***Note: Bollinger (1976) has restated the 1886 isoseismals to show intensity VII at the site, however, eyewitness accounts stated in the History of Hart County (Baker, 1933) allow no greater then intensity VI at the site. This agrees with Nuttli (1974) (Peak motions for intensity VII would be: 0 21 g, 25 cm/sec , 15 cm displ)



a. NEAR FIELD

b. FAR FIELD

Intensity Versus Acceleration (Horizontal) in the Near and Far Fields.

FIGURE 23

118. The distance from epicenter to the limit of the near field, and beginning of the far field, varies with the magnitude of the earthquake. Table 7 shows limits of the near field for various magnitudes and intensity levels of earthquakes.

Intensities Versus Peak Ground Motions.

119. Figures 24 and 25 show the relation between MM intensity and acceleration for near field and far field respectively. Figures 26 and 27 show intensity versus velocity, near and far field, and Figures 28 and 29 for displacement, near and far field. The motions are horizontal. Vertical components of motion are taken to be two-thirds the horizontal. The figures also show mean and mean plus one standard deviation for each intensity level. The projected lines of 10 percent increments show the spread between the mean (50 percent) and the maximum projected line or limit of observed data (100 percent). The projection of these lines is intended to compensate for the lack of data at higher intensity levels. Note that for near field acceleration, the mean plus one standard deviation declines from Intensity VII to Intensity VIII. The decline is because of a lack of data at Intensity VIII and not because the values should decline. The curves for these percentage increments are suitable for obtaining peak motions at levels selected either at the maximum or at lesser levels determined by decisions on the seismic risk that is acceptable.

120. No distinction was made between data from soil and rock since the values overlap too greatly to provide useful comparison. The figures are intended to provide peak components of ground motion on bedrock at the surface.

121. Table 6 shows peak motions for acceleration, velocity, and displacement that were selected for the major seismic risk zones. The motions are for the MM intensities at the sites. The appropriate field conditions are shown. The motions are based on the 70 to 80 percentage bands for the near field and for higher bands in the far field. See Figures 24 through 29.

122. Durations on Table 6 are obtained from the peak values on Figures 30 and 31.

Comparison With Alternative Methods.

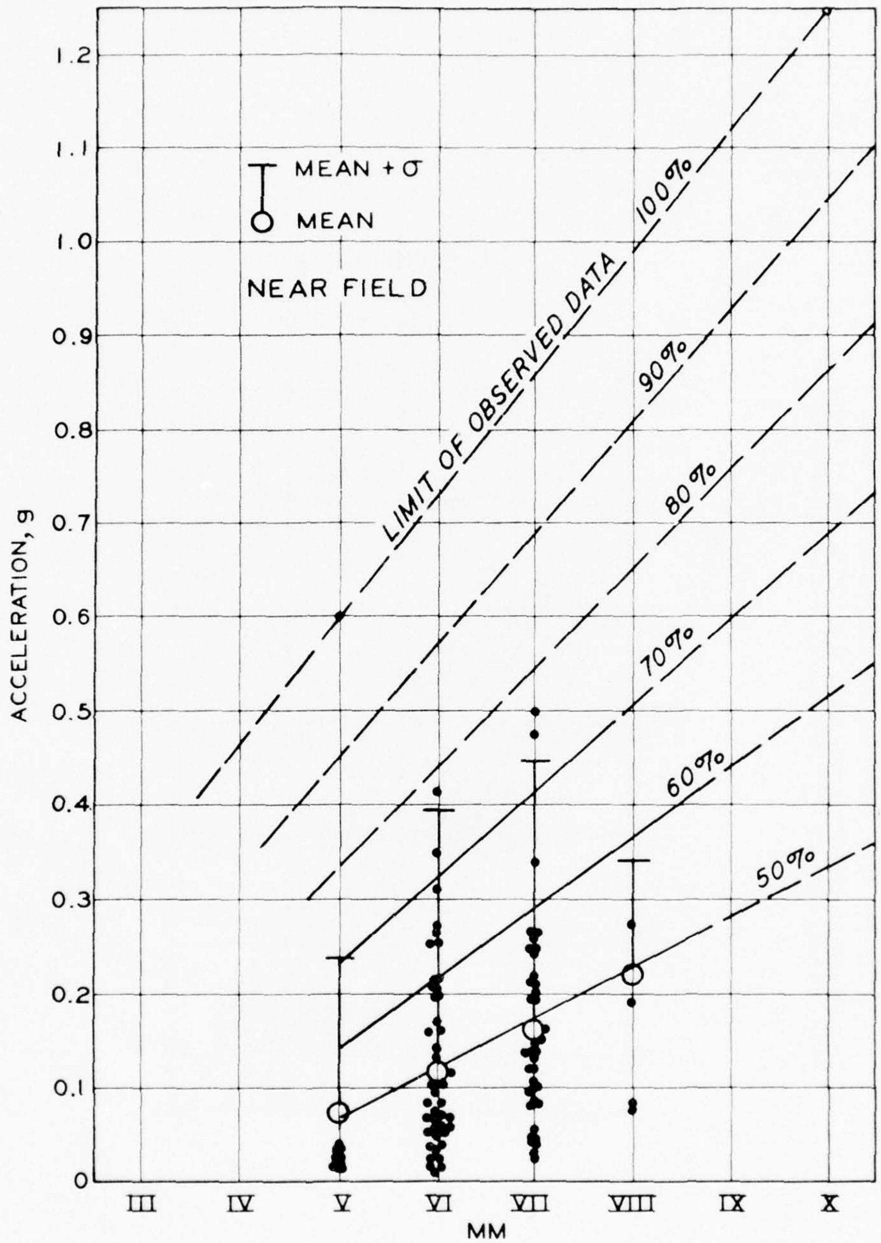
123. At this point, comparisons can be made with other methods that are used to obtain peak motions. Table 8 shows peak horizontal ground motions, interpreted from various authors, for bedrock at the Richard B. Russell site.

Intensity-Acceleration Correlations.

124. Commonly used correlations between intensity and acceleration are shown in Figure 32. Included are correlations established by

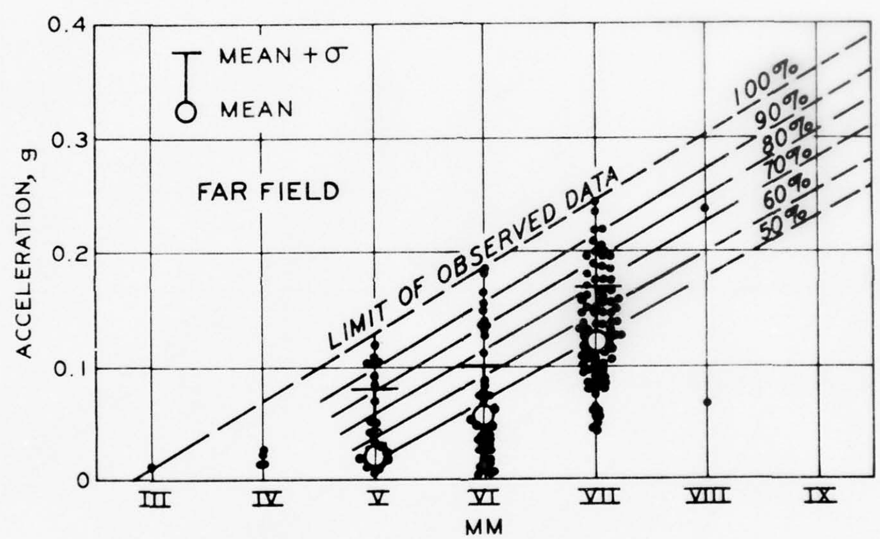
Table 7 Limits of the Near Field

Richter Magnitude	MM Maximum Intensity	Radius of Near Field (KM)
5.0	VI	5
5.5	VII	15
6.0	VIII	25
6.5	IX	35
7.0	X	40
7.5	XI	45



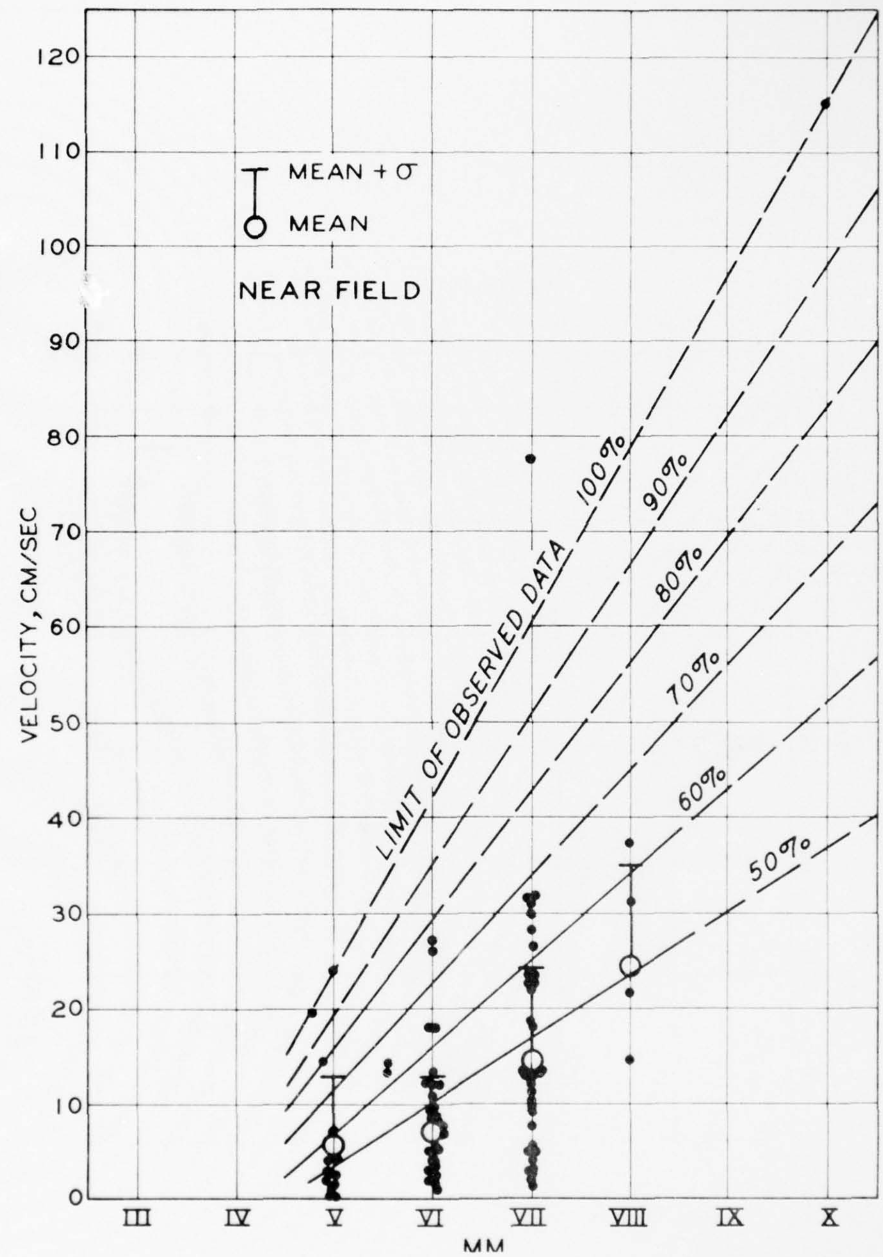
Acceleration Versus MM Intensity in the Near Field. Also Shown in the Mean, Mean plus One Standard Deviation, and 10 percent Increment Between the Projected Mean and the Limit of Observed Data (Krinitzsky and Chang).

FIGURE 24



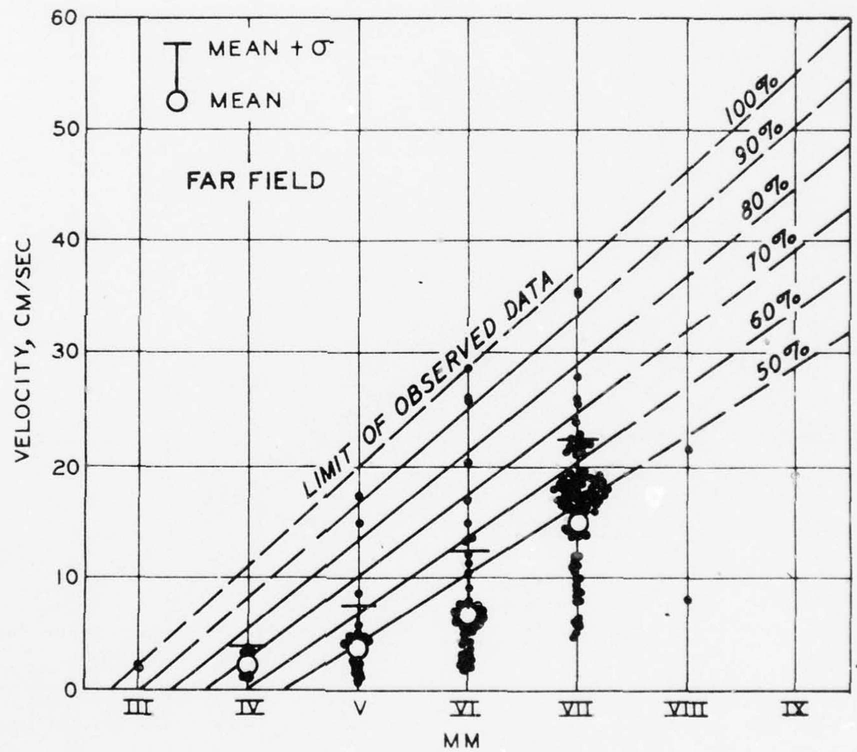
Acceleration Versus MM Intensity in the Far Field. Also Shown is the Mean, Mean plus One Standard Deviation, and 10 percent Increments Between Projected Mean and the Limit of Observed Data (Krinitzsky and Chang).

FIGURE 25



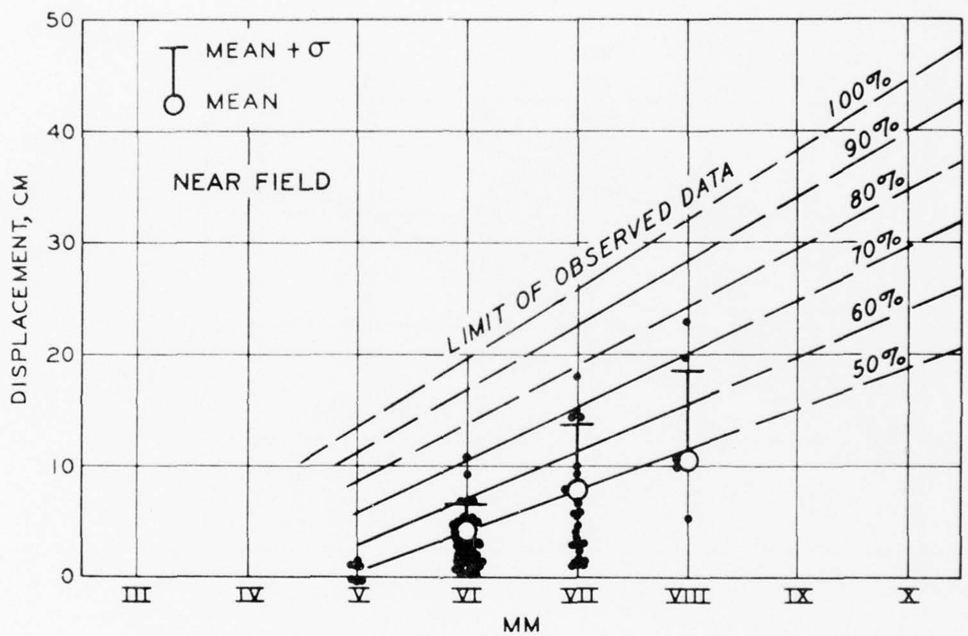
Velocity Versus MM Intensity in the Near Field. Also Shown is the Mean, Mean plus One Standard Deviation, and 10 percent Increments Between the Projected Mean and the Limit of Observed Data (Krinitzsky and Chang).

FIGURE 26



Velocity Versus MM Intensity in the Far Field. Also Shown is the Mean, Mean plus One Standard Deviation, and 10 percent Increments Between the Projected Mean and the Limit of Observed Data.(Krinitzsky and Chang).

FIGURE 27



Displacement Versus MM Intensity in the Near Field. Also Shown is the Mean, Mean plus One Standard Deviation, and 10 percent Increments between the Projected Mean and the Limit of Observed Data (Krinitzsky and Chang).

FIGURE 28

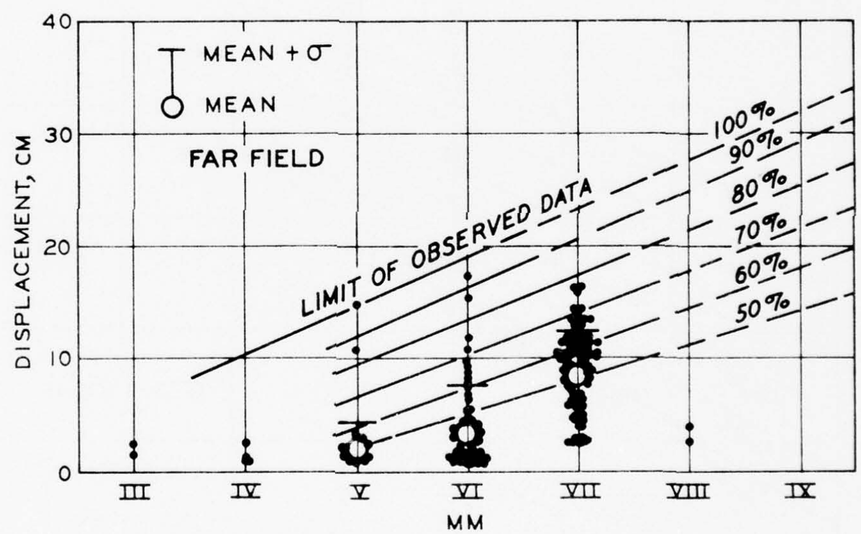
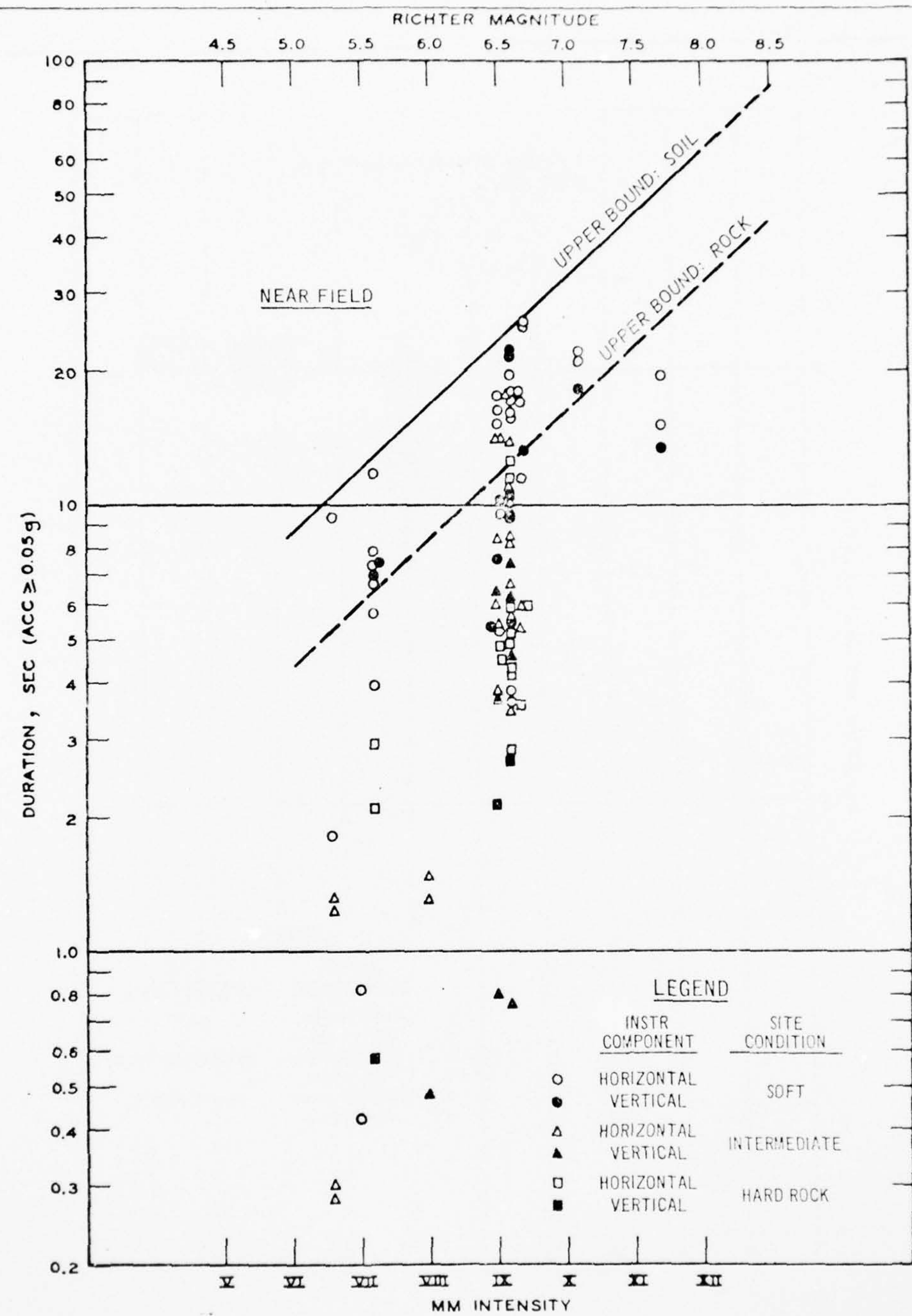


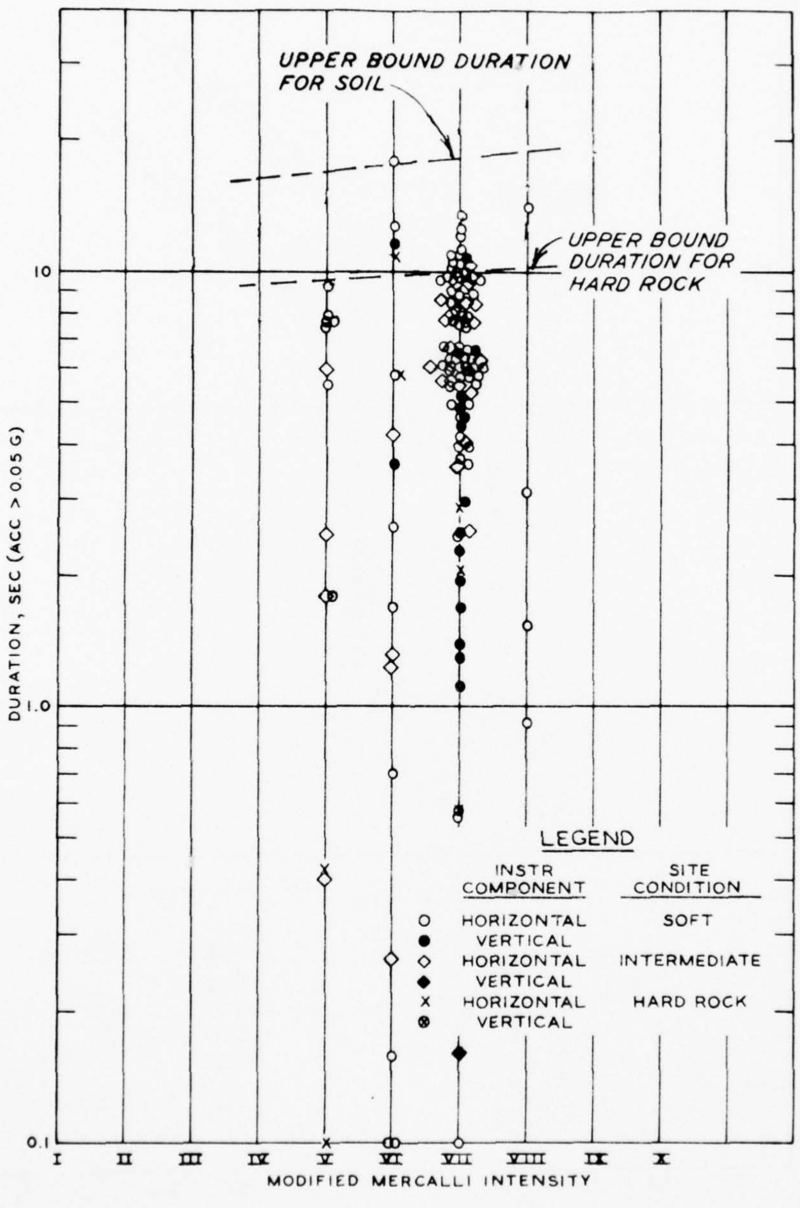
Figure 29 Displacement Versus MM Intensity in the Far Field. Also Shown is the Mean, Mean plus One Standard Deviation, and 10 percent Increments Between the Projected Mean and the Limit of Observed Data (Krinitzsky and Chang).

FIGURE 29



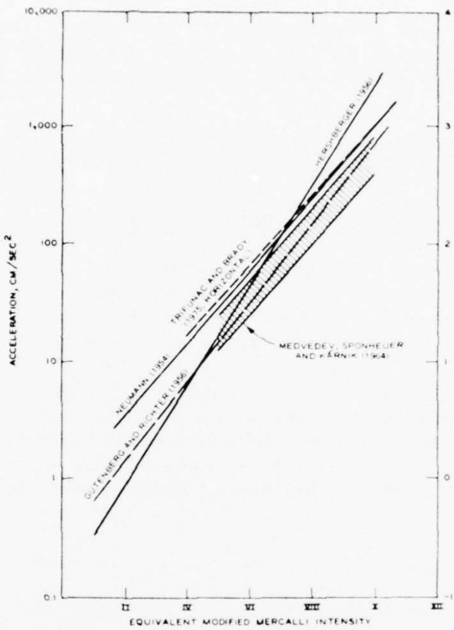
Duration Versus MM Intensity in the Near Field (Krinitzsky and Chang).

FIGURE 30



Duration Versus MM Intensity in the Far Field (Krinitzsky and Chang).

FIGURE 31



Commonly Used Correlations Between Intensity and Acceleration.

FIGURE 32

Neumann (1954), Gutenberg and Richter (1956), Hershberger (1956), Medvedev, Sponheuer, Karnik (see Barosh, 1969), and Trifunac and Brady (1975). (Trifunac and Brady also represent mean plus one standard deviation, plus other values, discussed later.) All of these curves in Figure 32 are either mean or average values made with various levels of data accumulation. They do not provide for the spread in data, and they do not distinguish between near field and far field conditions.

125. For MM VII at the site, the above correlations give 0.04g to 0.1g. The value used in this report is a range of 0.4 to 0.5g. For MM VI, the curves give 0.02 to 0.07g compared with 0.18g maximum in this report.

126. Values in this report are believed to be more realistic and are more conservative than those which are obtained using mean values.

Nuttli's Studies for Central United States.

127. Nuttli (1973) developed ground motions for various levels of earthquakes in central United States and for varying distances from epicentral areas. His motions are specified for .3, 1, and 3 Herz waves. Maximum motions from Nuttli are shown on Table 8.

128. Nuttli's motions are peak recurrent values, and they are resultant motions rather than horizontal motions. Resonance effects and the buildup of motions from combinations of spectral components were not assessed in Nuttli's tables. Consequently, his values are much lower, and consequently less conservative, than those used in this report.

Schnabel and Seed.

129. Schnabel and Seed (1973) provided values for maximum acceleration in rock for western United States. In the near field (see Figure 33), their curves show 0.38 to 0.52g for magnitude 5.6, equivalent to MM intensity VII. Their upper value of 0.52g compares favorably with the upper value of 0.5g obtained in this study.

130. For the far field, the Schnabel and Seed curves cannot be used for southeastern United States as the attenuation by distance is not comparable.

U.S. Geological Survey: Western United States.

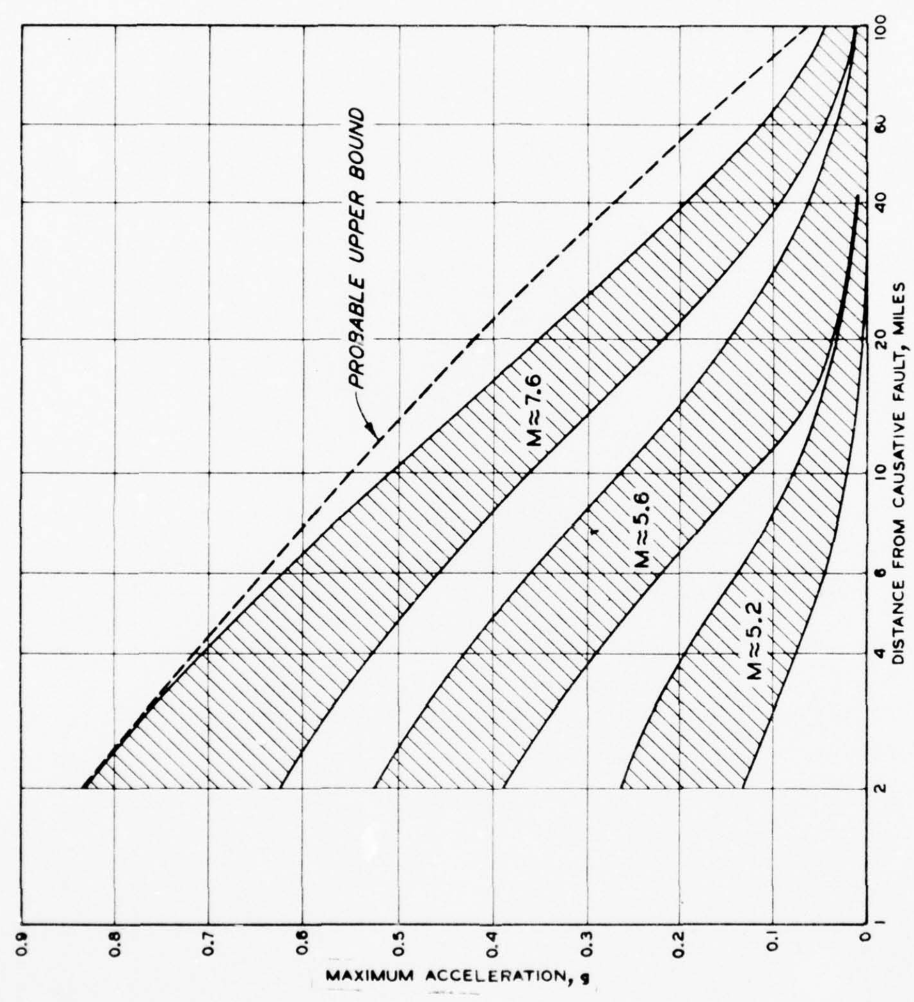
131. The Department of Interior Geological Survey data for selected earthquakes of the western United States (Page, et al, 1972) are shown in Figures 34 to 36. These relate accelerations, particle velocities, and displacements, respectively, to magnitude of earthquake and distance from source. These data were developed for studies related to

Table 8 Comparison of Peak Horizontal Ground Motions (Interpreted from Various Authors) for Bedrock at Richard B. Russell Damsite

Author	Intensity MM VII - Near Field Acceleration g*	Velocity cm/sec	Displacement cm	Duration sec	Intensity VI - Far Field Acceleration g	Velocity cm/sec	Displacement cm	Duration sec
Krinitzsky-Chang (this report)	0.5 (max)	30-45	20 (max)	5	0.18 (max)	20	12 (max)	9
Mean curves	0.04-0.1	---	---	---	0.02-0.07	---	---	---
Nuttli: Region 2, .3Hz, at 100 km or 62 miles (Charleston Earthquake)	---	---	---	---	0.083	4.1	2	---
Nuttli: Region 1, .3Hz, at 8 km or 5 miles	0.019-0.037	8.6-1.8	4.0-8.6	---	---	---	---	---
Schnabel-Seed	0.38-0.5	---	---	---	---	---	---	---
USGS-Western U. S.	0.5	72	22	10	---	---	---	---
USGS-Eastern U. S.	0.6	---	---	---	0.04	---	---	---
USGS-Algermissen-Perkins**	0.11	---	---	---	---	---	---	---
Trifunac & Brady mean + σ	0.13	14	20	---	0.11	11	9	---
Ambraseys	---	30	---	---	---	23	---	---
Bolt	---	---	---	8	---	---	---	---

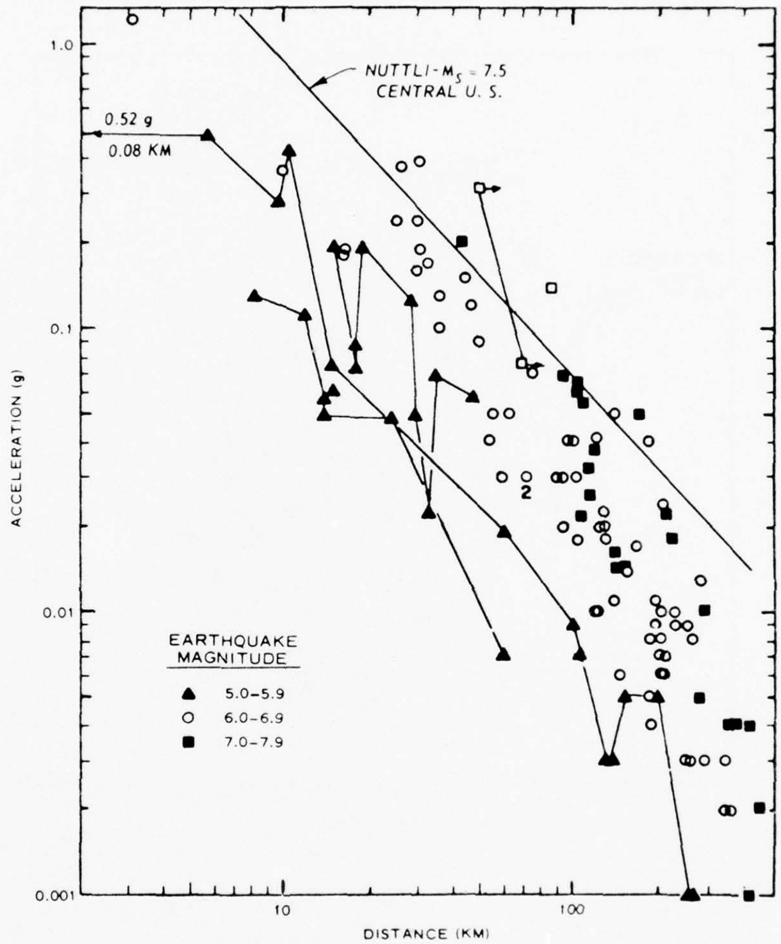
* 1g = 980 cm/sec^2

** 90 percent probability of not being exceeded in 50 years.



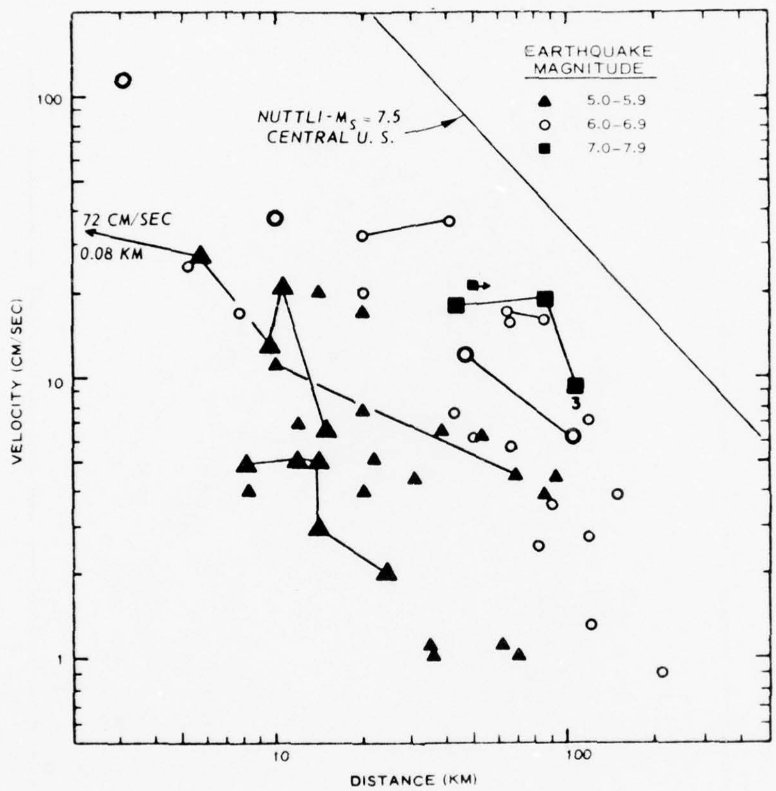
Ranges of Maximum Accelerations in Rock for the Western United States. Schnabel and Seed (1972)

FIGURE 33



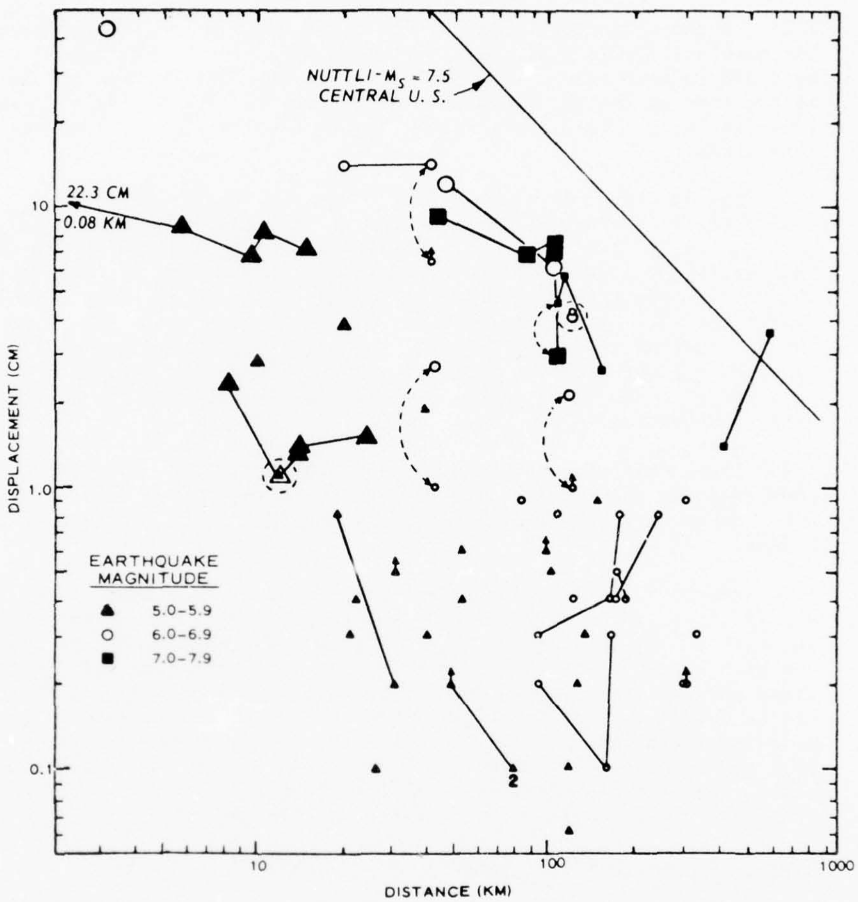
USGS Accelerations for Western United States Earthquakes.
Page, et al (1972)

FIGURE 34



USGS Velocities for Western United States Earthquakes. Page, et al (1972)

FIGURE 35



USGS Displacements for Western United States Earthquakes.
Page, et al. (1972)

FIGURE 36

the Trans-Alaska Pipeline. Superimposed are lines taken from Nuttli (1973) which represent a maximum New Madrid earthquake for the central United States with a magnitude of 7.5.

132. In the epicentral area for the magnitude 5.0 to 5.9 earthquake, the acceleration is 0.5g, directly comparable to the maximum value selected in this study. The Geological Survey displacement of 22 cm is the same as the 20 cm maximum in this study. The Geological Survey velocity is 72 cm/sec, appreciably higher than the 30 to 45 cm/sec of this study.

133. The 72 cm/sec is taken from the Cholame Shandon Array No. 2 of the Parkfield earthquake located 0.08 km from the movement on the San Andreas fault. The California Institute of Technology (1971-1975) compilation of strong motion records lists this motion at 77.9 cm/sec. Figure 26 shows this peak velocity corresponding to an assumed MM Intensity of VII. The data point is so extraneous to all the rest of the data for MM Intensity VII that the point has been discounted. The 70 to 80 percent band was used to arrive at 30 to 45 cm/sec. It is believed that the lower values accepted for in this report are still very conservative.

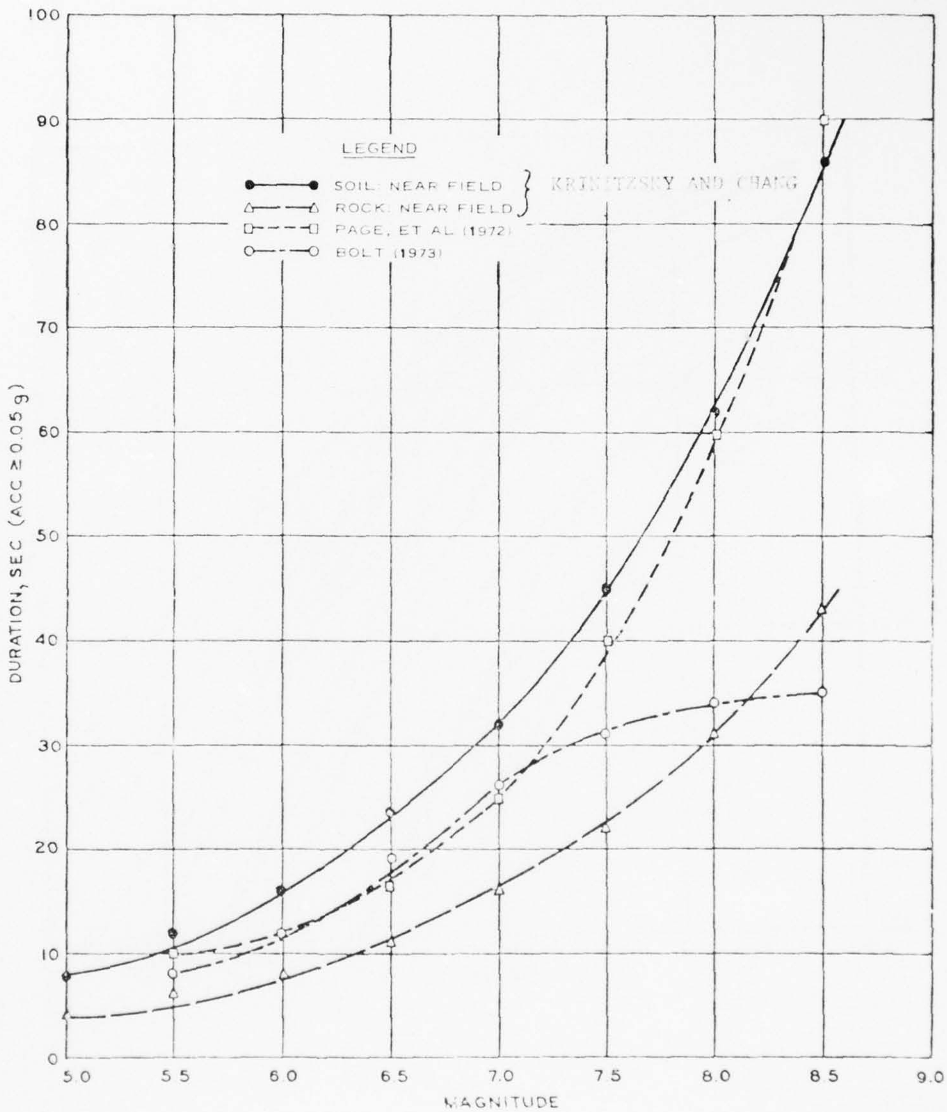
134. These USGS charts have not been compared for the far field conditions at the Russell site because the attenuations with distance are greatly different in the southeast from those in western United States.

135. Figure 37 shows a comparison between USGS durations (Page, et al, 1972) and those of Krinitzsky and Chang (1977, in preparation), and Bolt (1974) for the near field for various magnitudes of earthquakes. Durations in this report are bracketed durations of accelerations greater than 0.05g. For magnitude 5.5, the USGS duration of 10 sec is double that of Krinitzsky-Chang which is 5 sec. Bolt is intermediate with 8 sec. The Krinitzsky-Chang durations used in this report separate soil and rock. Rock has roughly half the duration of soil. The USGS has not used this separation and their value represents all data. Their value is unnecessarily conservative.

U.S. Geological Survey: Eastern United States.

136. For the eastern United States, the U.S. Geological Survey (1975) uses the distance versus acceleration graph shown in Figure 38. The curves (solid lines) are taken from Schnabel and Seed (1973) and were modified (dashed lines) by attenuating the lines according to the attenuations of Nuttli (1973) for the central United States.

137. The USGS peak acceleration for the near field is 0.6g, comparable to the upper value of this study. For the far field (100 km with a magnitude of 5.6), the USGS has 0.04g compared to 0.18g maximum.



4

Comparison of Near Field Durations with Page, et al, (1972), Bolt (1974)

FIGURE 37

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GEOLOGICAL AND SEISMOLOGICAL EVALUATION OF EARTHQUAKE HAZARDS A--ETC(U)

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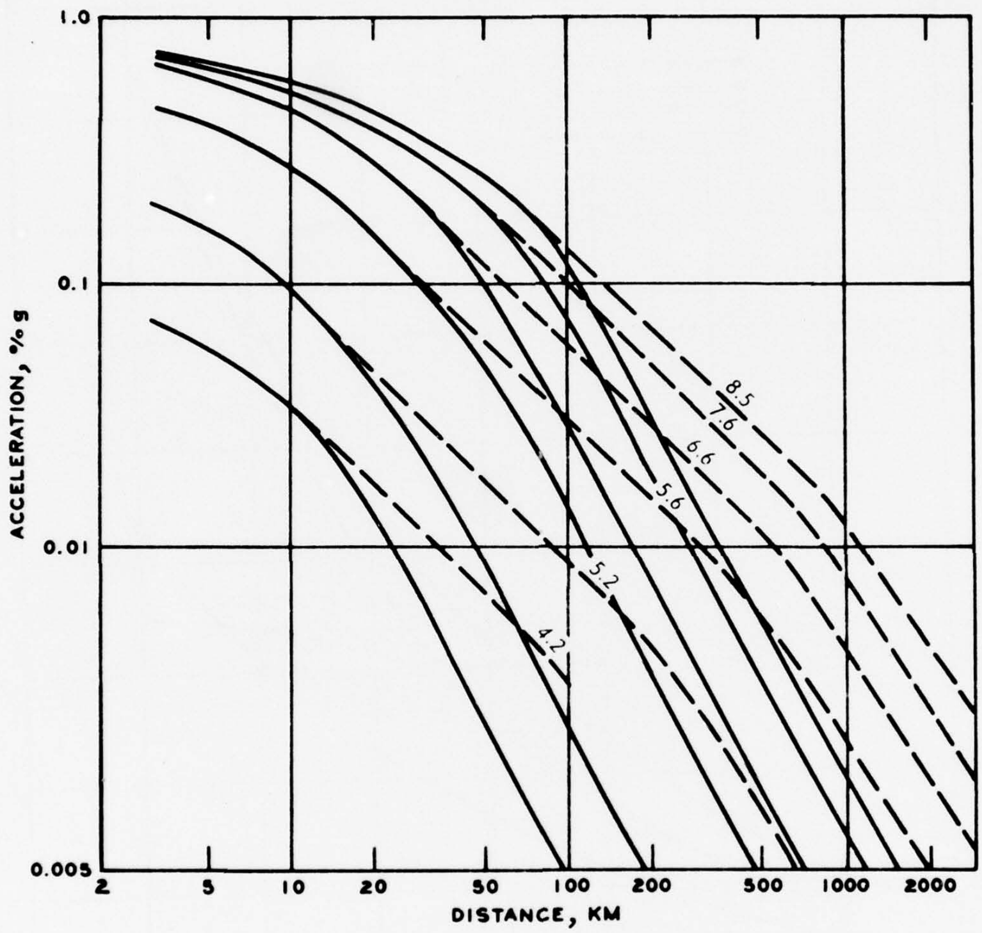


USGS Accelerations for the Eastern United States. The Lines are Those of Schnabel and Seed and Were Modified (dashed lines) by Imposing the Attenuations of Nuttli for Central United States. Schnabel and Seed (1972) Nuttli (1973)

FIGURE 38

Trifunac and Brady.

138. The values generated by Trifunac and Brady (1975) for ground motions in relation to intensity for the western United States are shown in Figure 39. The values do not distinguish between near field and far field as was done in this report. Otherwise, the data used by Trifunac and Brady and in this report are the same.

139. The values of Trifunac and Brady for one standard deviation on the plus side for a near field Intensity VII are much less than those used in this report. It is the same for the far field Intensity VI. The Trifunac and Brady values are handled in a purely statistical manner and do not reflect the interpretative handling they were given in this report.

Ambraseys.

140. Ambraseys (see Johnson and Heller, 1974) has reasoned that there is no upper bound to ground acceleration, but that particle velocity has an upper bound. Ambraseys developed an empirical equation for the relationship between the peak particle velocity, the magnitude of an earthquake, and the distance from the focus which was developed for epicentral distances of 10 to 150 km and magnitudes 5 to 7. Figure 40 shows maximum values for the above relationships. Ambraseys values both for the near field and far field closely approximate those developed in this report.

USGS: Algermissen and Perkins.

141. Algermissen and Perkins (1976) have developed a contour map of the United States which shows acceleration as a percent of g with a 90 percent probability of not being exceeded in 50 years. For the Russell site, their value is 0.11g.

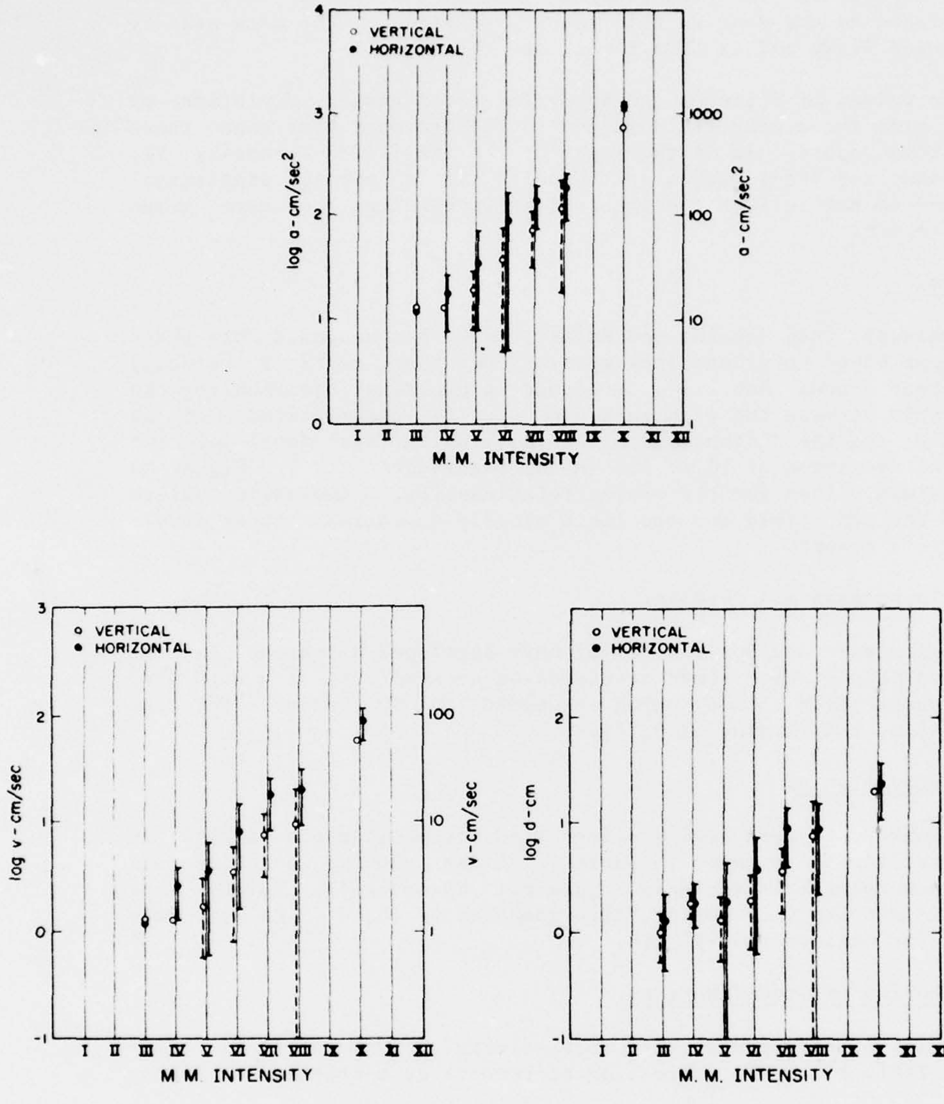
Nuclear Powerplants.

142. A summary of peak accelerations used for nuclear powerplants in the general region is shown in Table 9. A map showing locations of nuclear powerplants is shown in Figure 41. Essentially, values used in this report are very conservative compared to those which have been accepted for nuclear powerplants.

Time Histories of Ground Motions.

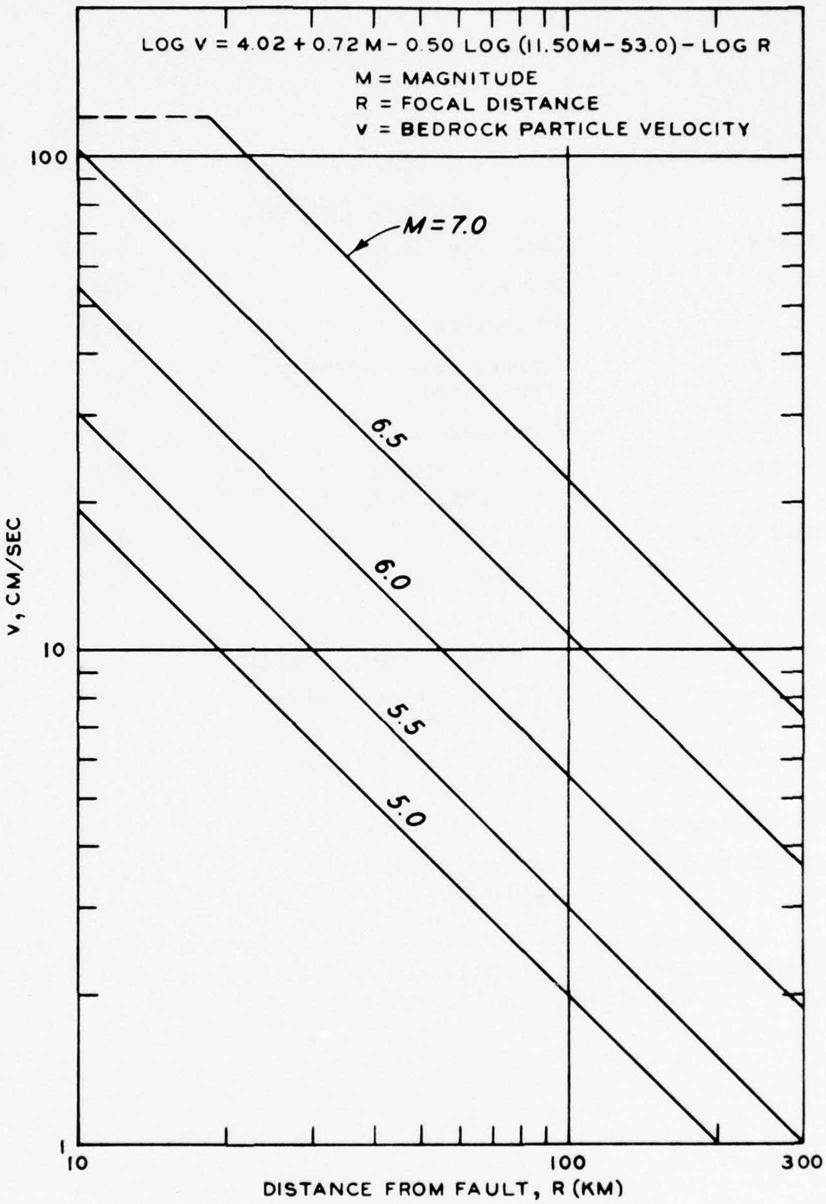
143. A list of strong motion records selected for rescaling is tabulated in Table 10. The collection of records is contained in Appendix 2.

144. The scaling factor in Table 10 is based on the peak motions listed in Table 8. The factor is based on scaling of velocity; for



Ground Motions Versus Intensity for the Western United States by Trifunac and Brady. Means (vertical and horizontal) plus and minus One Standard Deviation are shown for (a) Acceleration, (b) Velocity, and (c) Displacement. Trifunac and Brady(1975)

FIGURE 39



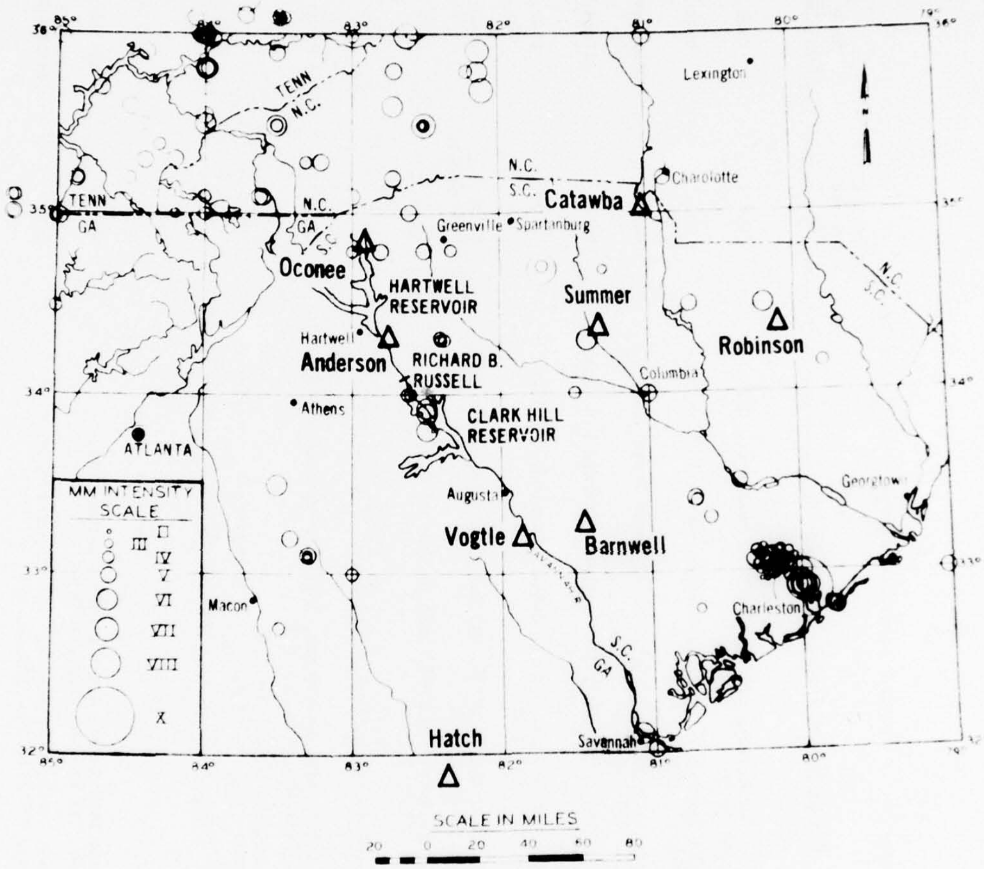
Maximum Probable Ground Velocities by Ambraseys (from Johnson and Heller, 1974).

FIGURE 40

Table 9 Nuclear Plant Seismic Designs

Plant	Material	DBE/SSE* Accel, g	OBE* Accel, g
	Piedmont Province		
Catawba	Continuous rock	0.15	0.08
Oconee	Bedrock	0.10	0.05
	Overburden	0.15	----
McGuire	Jointed rock, slightly weathered	0.15	0.08
Anderson	Firm bedrock	0.14	0.07
Cherokee	Closely jointed, weathered rock	0.15	0.08
Virgil C. Summer	Rock	0.15	0.10
	Residual soil	0.25	0.15
	Coastal Plain Province		
Barnwell	Soft sedimentary rocks and soils	0.20	0.12
Edwin I. Hatch	Soft sedimentary rocks and soils	0.15	0.08
H. B. Robinson	----------	0.20	0.10
Alvin W. Vogtle	Soft sedimentary rocks and soils	0.20	0.12

* DBE/SSE - Design Basis Earthquake or Safe Shutdown Earthquake
  OBE - Operating Basis Earthquake



NUCLEAR PLANTS NEAR PROJECT SITE

Nuclear Plants near Project Site.

FIGURE 41

Table 1[illegible] Selected Earthquake Records With Scaling Factors

Earthquakes	Strong Motion Record for Rescaling	Epicentral Distance km	Site Condition	Scaling Factor For Velocity
PIEDMONT EARTHQUAKE				
Reverse Fault	1. San Fernando Earthquake, 2/9/71, Griffith Park Obs., CIT File No. 0198, S 00 W	34.0	Rock	2X
	2. San Fernando Earthquake, 2/9/71, Pacoima Dam, CIT File No. C041, S 16 E	9.1	Rock	1/3X
	3. San Fernando Earthquake, 2/9/71, 445 Figueroa Street, L.A., CIT File No. C054, N 52 W	41.9	Intermediate	2X
	4. San Fernando Earthquake, 2/9/71, Hollywood Storage P.E. Lot, L.A., CIT File No. D058, N 90 E	37.1	Alluvium	2X
	5. San Fernando Earthquake, 2/9/71, Castaic Station, CIT File No. D056, N 21 E and N 69 W	28.6	Rock	1 1/2X
Strike Slip	1. Parkfield Earthquake, 6/27/66, Cholame Shandon Array No. 2, CIT File No. B033, N 65 E	31.9 (0.08 from fault)	Rock	1/2X
	2. Parkfield Earthquake, 6/27/66, Temblor Station S 25 W CIT File No. B037, S 25 W	31	Rock	1 1/2X
Normal Fault	1. Helena, Montana, Earthquake, 10/31/35, CIT File No. D025, N 90 E	6.6	Rock	3X
	2. Oroville, California, Earthquake, 8/1/75, Component N 37 E or N 53 W, Peak Acc. = 0.10 - 0.11 g	12.0	Rock	4X
	3. Koyna Earthquake, India, M = 6.5 Longitudinal: a_{max} = .63 g; v_{max} = 32 cm/sec; d_{max} = 13.3 cm Transverse: a_{max} = .49 g; v_{max} = 20.08 cm/sec; d_{max} = 31.64 cm	5	Rock	1X
CHARLESTON AND NEW MADRID EARTHQUAKES				
	1. San Fernando Earthquake, 2/9/71, 1625 Olympic Blvd, Los Angeles, CIT File No. 0199, N 62 W	42	Alluvium	1X
	2. San Fernando Earthquake, 2/9/71, 3411 Wilshire Blvd, Los Angeles, CIT File No. S265, W	39.9	Intermediate	1X

example, the 30 to 45 cm/sec of the near field condition in the Piedmont. The "maximum" values for the accelerations and velocities represent motions that should be obtained by the scaling. Displacements are not critical for scaling.

Probabilistic Analysis of Earthquake Recurrence.

145. A report on probabilistic analysis of earthquake recurrence at the Richard B. Russell site is contained in Appendix 1.

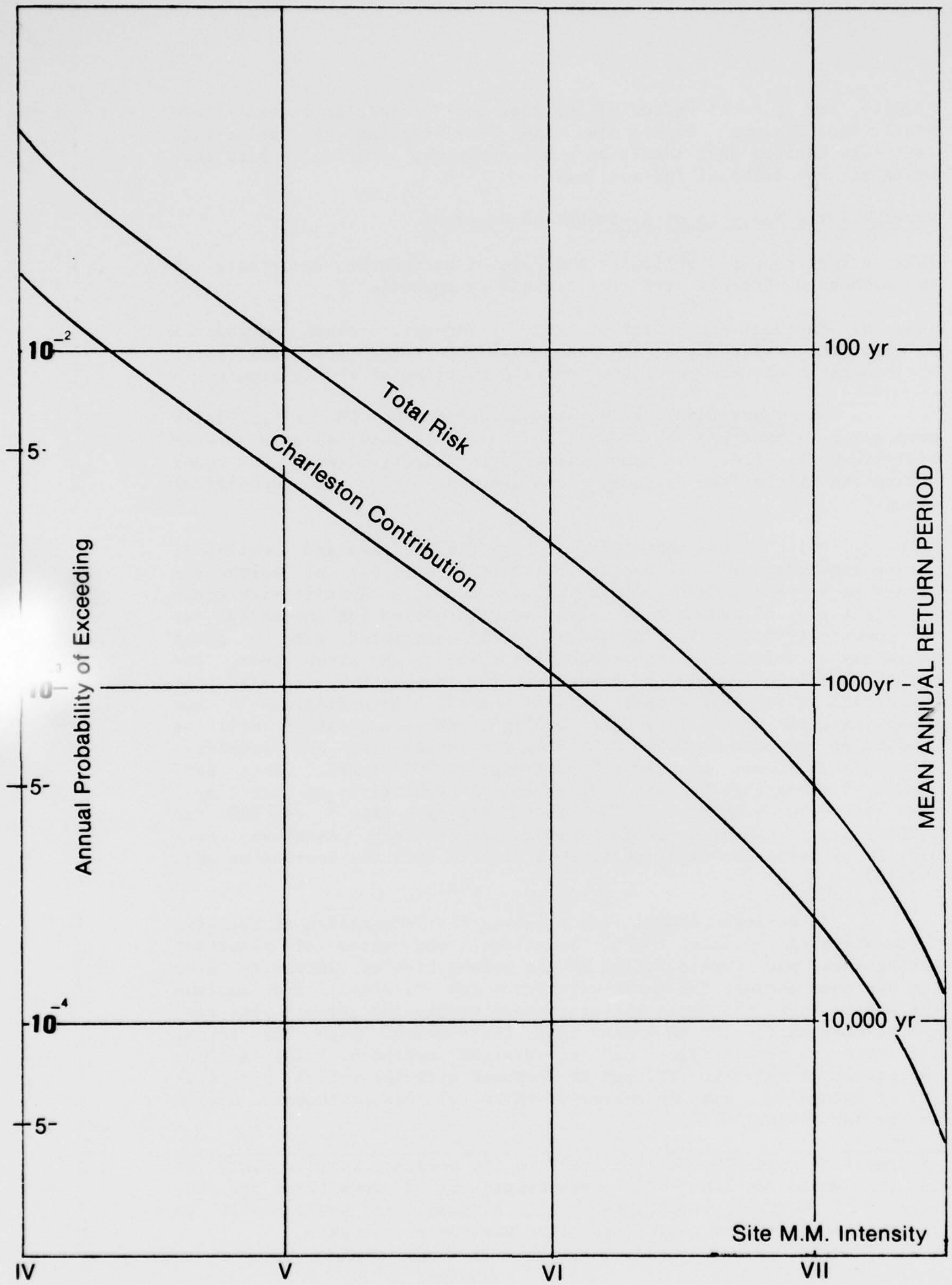
146. a. The peak acceleration for a 100-year return period is 0.075g. This value may be used as a basis for the operating basis earthquake in the design of the concrete portions of the structure.

b. The Operational Earthquake, as defined by CE is generally more moderate than the maximum earthquake and is selected on a probabilistic basis, i.e., the probability of the what is likely to occur during the life of the project, for use in design of noncritical items.*

c. Owing to the uncertainty in the number, size and location of future earthquakes, it is appropriate that an analysis of earthquake hazard be expressed by seismic risk. The output of seismic risk analysis is a plot of annual risk versus seismic motion (MM intensity) at the damsite (Figure 42). The annual risk associated with a given intensity is defined as the probability that, in any given year, the intensity will be equaled or exceeded. The annual risk is also the reciprocal of the mean annual return period. Accordingly, in any given year, the probability that 0.075g peak acceleration will be equaled or exceeded is 0.01; 0.0014 is the annual risk for acceleration of 0.2g (i.e., the mean return period is 700 years). Note that Figure 42 shows that the estimate of annual probability of exceeding a site intensity of MM VI is $3X10^{-3}$ and MM VII is $4.5X10^{-4}$, or 350 and 2,200 years mean annual return periods, respectively. As shown (Figure 42), a large contribution to this risk is from the Charleston area (62.5%).

d. To estimate annual risk requires the integration of relative frequencies of possible times, locations, and sizes of important earthquakes, plus consideration of the attenuation of intensity over the distance between the earthquake focus and the site. The maximum earthquake takes the worst historic event within the seismic risk zone and assumes this event to happen under the damsite. Both the former and latter is the practical and conservative approach. The maximum earthquake of intensity VII can be compared with the annual probability of exceeding a site intensity of MM VII if this earthquake occurs in the far field.

*Judgment of noncriticality is based on the premise that failure of the item would not lead to a catastropic flood downstream or the failure of pool containment; such failure items which would result in flooding are designed to withstand the maximum earthquake.



INTENSITY vs. ANNUAL RISK

FIGURE 42

PART VIII - SUMMARY AND CONCLUSIONS

147. No evidence of active faults is present in the general area of the damsite. It is concluded that the faults which are present are all ancient ones and are inactive. Present day tectonism indicates that moderate earthquakes occur in the Piedmont and adjacent regions. Severe earthquakes are restricted to a narrow band along the Summerville to Charleston, South Carolina, area. There the faults are obscured by Coastal Plain sediments. Motions attenuated from Summerville-Charleston band to the damsite are low.

148. Four seismic risk zones were assigned. These are the Blue Ridge, Piedmont, Coastal Plain, and Charleston-Summerville zones. The most severe condition is an earthquake at the damsite with a peak velocity of 30 to 45 cm/sec, 0.4 to 0.5g for acceleration, 20 cm approximate maximum for displacement, and 5 sec duration. (The panel determined these to be the peak motions for the design earthquake.) For purposes of design, to be most conservative is to assume that the maximum earthquake will occur under the dam. A group of time histories were selected for rescaling.

149. A probability of recurrence study showed that the operating earthquake has an acceleration of 0.075g (0.01 annual risk). The operating basis earthquake is generally more moderate than the maximum earthquake. It is selected on a probabilistic basis from regional and local geology and seismology studies as being the largest expected to occur during the life of the project; in this case, 100 years.

150. In this instance, this peak ground acceleration is considerably smaller than the design value of the Richard B. Russell Dam. In other words, the dam is designed to withstand an earthquake several times stronger than would be expected to occur during its useful life.

151. In all likelyhood, the lake impounded by Russell Dam will not itself produce a damaging earthquake. Furthermore, any earthquake or one that could conceivably be produced by the lake will not exceed the natural maximum earthquake for the region.

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GEOLOGICAL AND SEISMOLOGICAL

EVALUATION OF EARTHQUAKE HAZARDS

AT

THE RICHARD B. RUSSELL PROJECT

APPENDIX 1

TECHNICAL REPORTS

SECTION A

Short-Period Surface-Wave Attenuation and Intensities in the Georgia-South Carolina Piedmont Province

Short-Period Surface-Wave Attenuation
and Intensities in the Georgia-South
Carolina Piedmont Province

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Short-Period Surface-Wave Attenuation

and

Intensities in the Georgia-South Carolina Piedmont Province

Leland Timothy Long

Abstract

The decay with distance of the maximum particle velocity "A" in mm/sec for quarry explosions and earthquakes follows the equation:

$$\text{Log} (A) = -1.5 - 2.0 \text{ Log} (D) + M_L$$

where D is in kilometers and M_L is the Richter magnitude as defined at 100 km. This equation is valid only in the range of 20 to 150 km for events with travel paths contained entirely within the Piedmont Province of Georgia and South Carolina. If needed, intensities from a magnitude $2.0 < M_L < 5.5$ event can be obtained by conversion of the particle velocities to intensity by use of the relations given by Nuttli (1973).

Introduction

The evaluation of seismic risk inherently involves the computation of the intensity to be expected from an event at distance. This computation requires some knowledge of the decay of seismic waves with distance and the relation of seismic wave amplitudes to observed intensities. Most studies show a considerable scatter in the relations between measured parameters and intensity. However, the scatter can usually be attributed to variations in near-surface soil types or crustal structure. By contrast, in the Georgia and South Carolina Piedmont Provinces the near-surface soil types and crustal structures are relatively uniform. The object of this paper is to derive a particle velocity versus distance relation from quarry explosion amplitudes and discuss their implication for intensity data in the distance range of 10

to 150 kilometers in the Georgia and South Carolina Piedmont Province.

Quarry Explosion Data

For both quarry explosions and earthquakes which occur and are recorded within the Piedmont Province at distances less than 150 kilometers, the largest amplitude arrival on the ATL station records is either a normally-dispersed Rayleigh or Love wave with a period of 0.2 to 2 seconds. Events from outside the Piedmont Province or Piedmont Province events recorded outside the Province seldom show these phases. The maximum Love and Rayleigh surface-wave amplitudes observed on the ATL seismograms were measured for four quarries and over 100 explosions. The four quarries were at distances of 25 km (Red Oak), 55 km (Norcross), 70 km (Kennesaw) and 150 km (Elberton).

The trace amplitudes (Peak to Peak) observed at the Red Oak Quarry (Figure 1) show a considerable scatter when plotted against charge size in pounds of explosive. However, records of events with large Rayleigh wave amplitudes usually showed small Love wave amplitudes and vice-versa, indicating a variation in the excitation of these phases. The azimuthal variation in the excitation of these phases is attributed to the orientation of the quarry face relative to ATL and the inherent asymetry of such explosions. A significant reduction in the scatter is achieved by computing the vector sum of Rayleigh and Love wave amplitudes (Figure 2). A least square's straight-line fit to the Red Oak amplitude data in figure 2 gives a 20 mm (0 to peak) ATL trace amplitude at 2.0 Hz for a charge size of 10,000 lb of explosive. Similar analyses of data from the Norcross (Figure 3) and Kennesaw (Figure 4) quarries indicate trace amplitudes of 6 mm at 1.7 Hz and 3.5 mm at 1.5 Hz trace amplitudes (0 to peak) respectfully. Three quarry explosions from Elberton, Georgia at a distance of 150 km give a 0.9 mm trace amplitude at ATL for 1.3 Hz waves. The trace amplitudes were converted to particle velocity by multiplication by

$2\pi f/50{,}000$ (gain at ATL is 50,000) and are listed in Table I. A plot of distance versus amplitude (Figure 5) shows that the data for the equivalent of 10,000 lb of explosive are satisfied by the equation

$$\text{Log}(A) = 0.5 - 2.0\,\text{Log}(D),$$

where, A = maximum particle velocity (mm/sec) for 10,000 lb explosive

and D = distance in kilometers ($10<D<150$)

in the Piedmont Province.

If the definition of local magnitude (Richter, 1958) is applied to the maximum displacement at 100 km observed for the quarry explosions, then a 10,000 lb explosive is equivalent to a magnitude 2.0 event. Within the distance range of 20 to 100 km and within the uncertainty in the data (estimated at $\pm$ 25% for one standard deviation) the slope is identical to the slope of the Richter (1958) local magnitude standard amplitude values.

Intensity Data

Intensity maps from the South Carolina earthquakes of January 1, 1913 (Taber, 1913), July 13, 1971 (Bollinger, 1972) and August 2, 1974 (Bridges, 1975) were used to measure mean radius of felt areas in the Piedmont Province for various intensity levels. The contours lines were assumed to enclose observations of the intensity given. The mean radius of the felt areas can then be interpreted as the distance to an intensity equivalent to half a unit lower than indicated for the felt area. These intensity values were then converted to particle velocity by using relations presented by Nuttli (1973). Nuttli's relations are considered appropriate since the partical velocities used for correlation with intensity were obtained from observatory data in the eastern United States. The data of this study are given in Table I. The resulting partical velocities were than normalized to a constant value (0.0035 mm/sec) at 30 km distance for plotting on Figure 5 with the quarry

data. The intensity data for the July 13, 1971 event were supplemented by the observed amplitude at ATL. The RF intensities for the January 1, 1913 earthquake were converted to MM prior to computation of particle velocities. The decay of the Intensity data is remarkably consistant with the measured quarry explosion amplitudes. Hence, for the Piedmont Province, this relation would be appropriate for computing intensities for known magnitude events. The magnitude (see Table 1) can be computed from the normalization factors for the events studied by using the generalized form of the equation for maximum particle velocity versus distance,

$$\text{Log}_{10} (A) = -1.5 - 2.0 \text{ Log} (D) + M_L$$

where A = maximum particle velocity for event of Local magnitude M_L

and D = distance in kilometers ($10<D<150$)

Discussion and Conclusions

Given a measure of an earthquake's magnitude (M_L) as defined by Richter (1958) at 100 km, the equation derived above for particle velocity versus distance can be used to predict the intensity to be expected at distances of 10 to 150 kilometers. The decay rate is notable more rapid than previously reported for eastern United States earthquakes (Nuttli, 1973). However, the distances are shorter than the distances studied by Nuttli (1973). Also, beyond 150 km in the Piedmont Province the shear phase or Lg phase has the greatest amplitude rather than the short period Rayleigh or Love arrival. The distance decay of the shear or Lg is significantly less than observed for short periods surface phases. Consequently, this relation should not be used beyond 150 km.

Acknowledgements

This research was supported by the National Science Foundation through Grant Number GA31962.

Table 1

Event	Frequency Intensity	MM*	Distance (Km)	Particle Velocity (mm/sec)	Normalization Factor	Magnitude M_L
RED OAK	(2.0 Hz)		25	0.0050	1.0	2.0
NORCROSS	(1.7 Hz)		55	0.0012		
KENNESAW	(1.5 Hz)		70	0.00067		
ELBERTON	(1.3 Hz)		150	0.00014		
			(30)	(0.0035)		
	Intensity					
July 13,	IV MM		10	2.0	.0078	4.1
1971	I MM		40	0.3		
(ATL)	1.2 Hz		200	0.015		
			(30)	(0.45)		
August 2,	V MM		13	3.8	.001667	4.8
1974	IV		32	2.0		
			(30)	(2.1)		
January 1,	VIII RF	VII	10	28	.00035	5.45
1913	VII RF	VI	25	14		
	VI RF	V-VI	45	5		
	V RF	IV-V	75	2.5		
			(30)	(10)		

*Original ratings were in Rossi-Forel - MM intensities are converted by Krinitzsky.

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Figure Captions

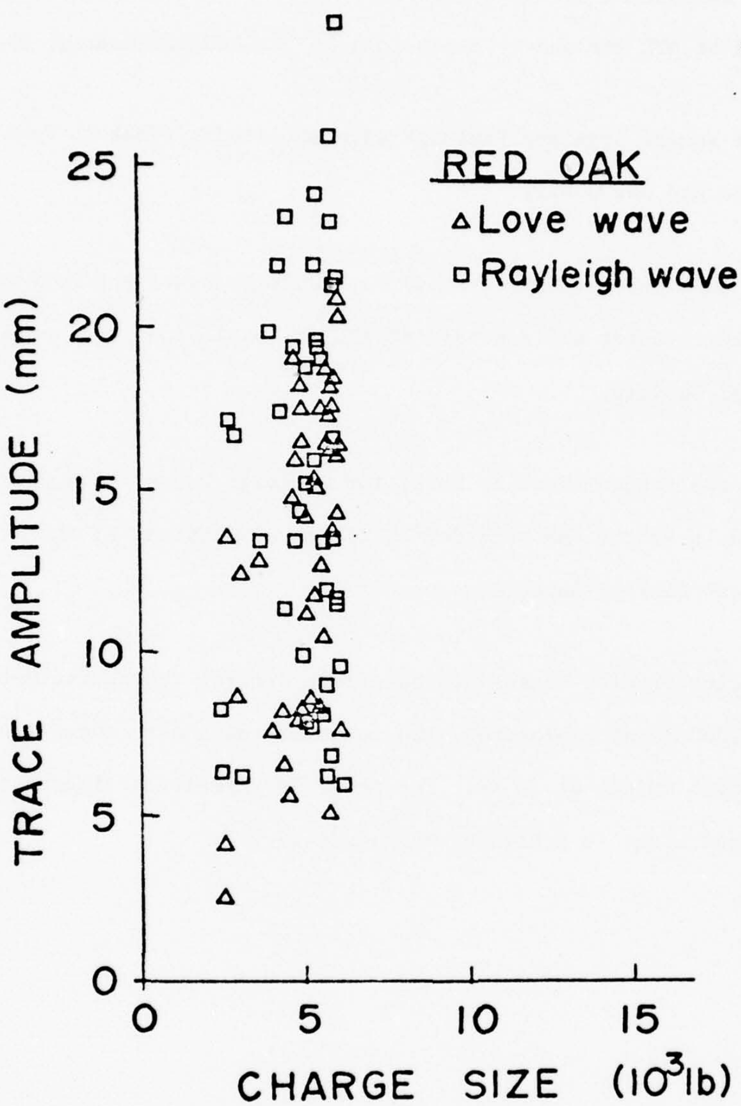
Fig. 1. Trace amplitudes (Peak to Peak) for Rayleigh and Love waves recorded at ATL for quarry explosions at the Red Oak Quarry, Ga.

Fig. 2. Vector sum of Love and Rayleigh wave amplitudes (Peak to Peak) for the Red Oak Quarry.

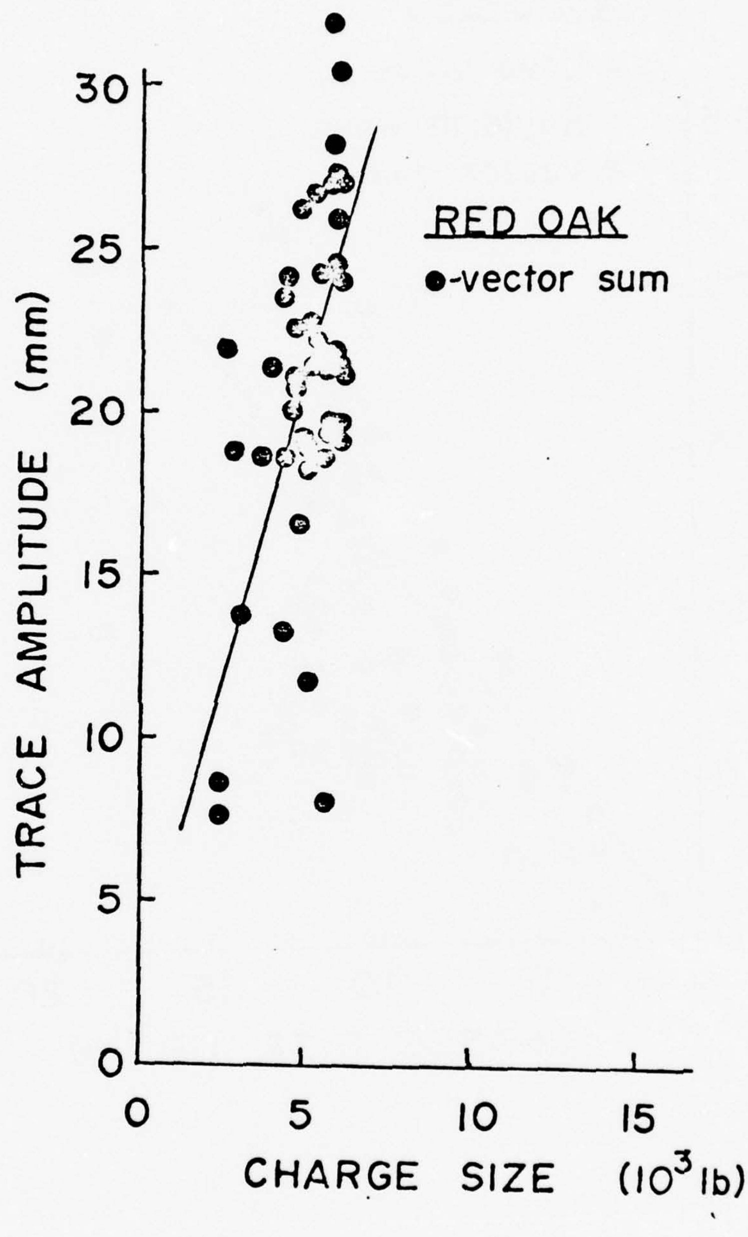
Fig. 3. Trace amplitudes (Peak to Peak) for Rayleigh waves and Love waves and their vector sum recorded at ATL for explosions at the Norcross Quarry, Georgia.

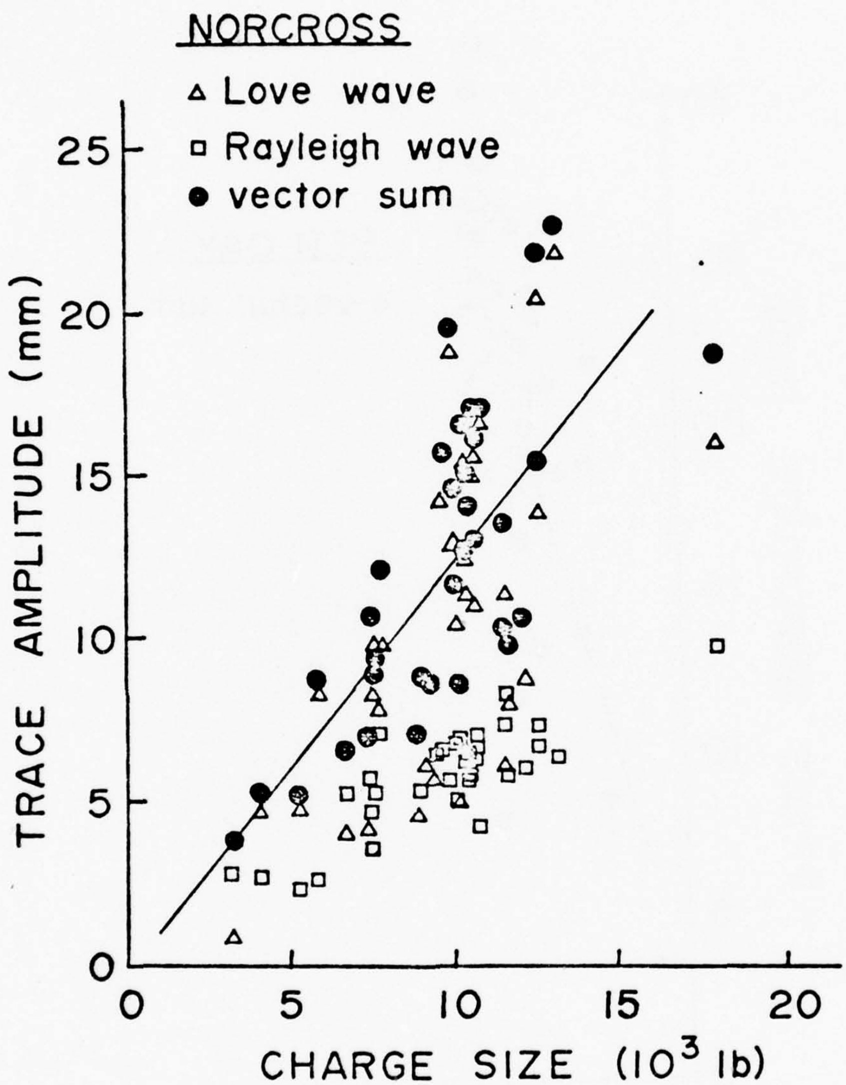
Fig. 4. Trace amplitudes (Peak to Peak) for Rayleigh waves, Love waves and their vector sum recorded at ATL for explosions at the Kennesaw Quarry, Georgia.

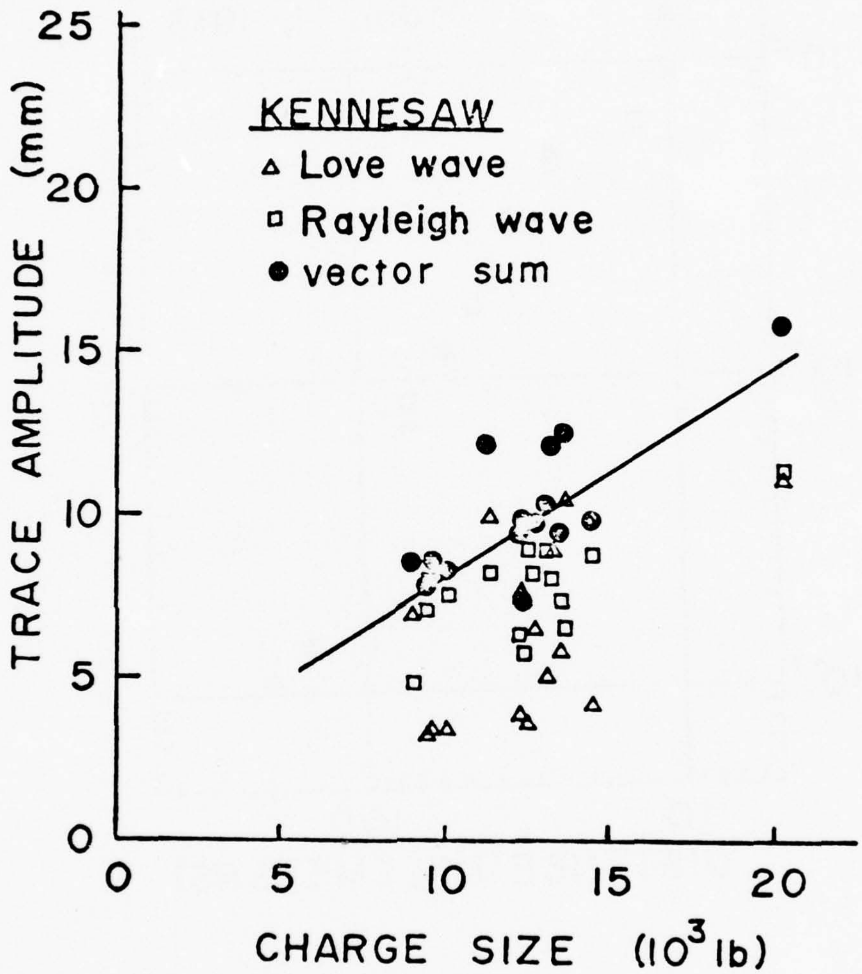
Fig. 5. Particle velocity versus distance relation for the equivalent of 10,000 lb of explosive. The intensity data were normalized to 0.0035 mm/sec at 30 km. The particle velocities illustrated are equivalent to a Richter magnitude of 2.0.

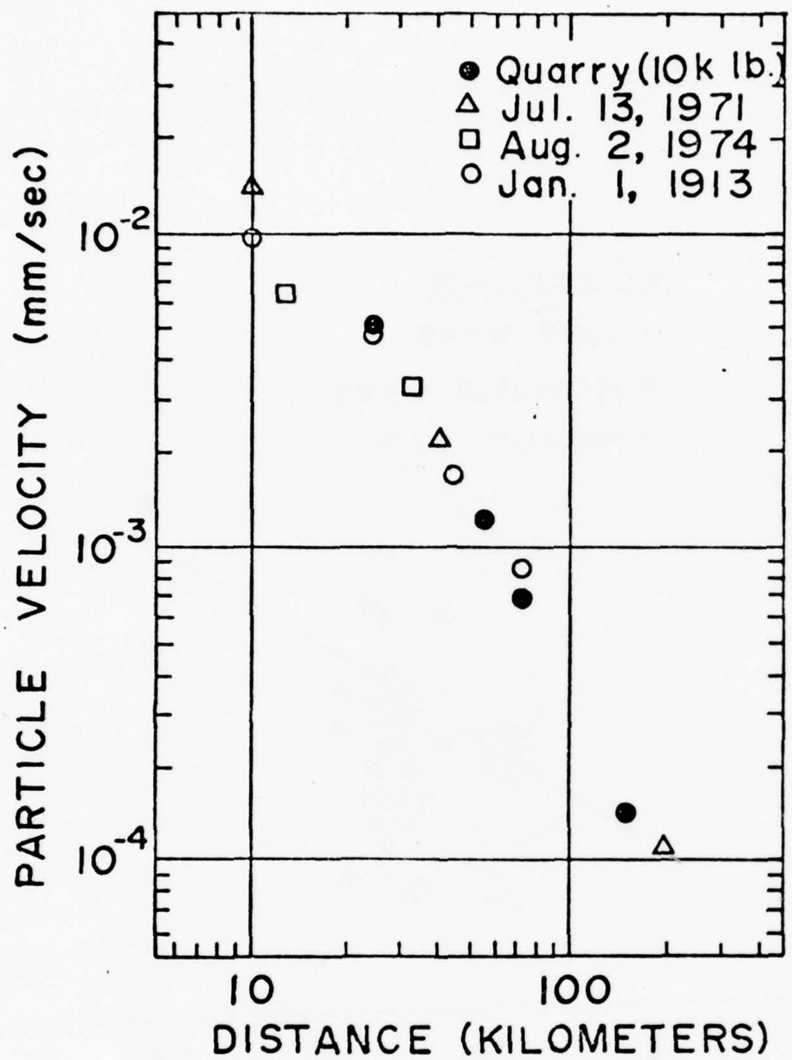


RED OAK
Love wave
Rayleigh wave
TRACE AMPLITUDE (mm)
CHARGE SIZE (10^3 lb)
0
5
10
15
20
25


TRACE AMPLITUDE (mm)
30
25
20
15
10
5
0
0
5
10
15
CHARGE SIZE (10^3 lb)
RED OAK
●-vector sum


NORCROSS
Love wave
Rayleigh wave
vector sum
TRACE AMPLITUDE (mm)
CHARGE SIZE (10^3 lb)
0
5
10
15
20
25


KENNESAW
Love wave
Rayleigh wave
vector sum
TRACE AMPLITUDE (mm)
CHARGE SIZE (10^3 lb)
0
5
10
15
20
25



Quarry (10k lb.)
Jul. 13, 1971
Aug. 2, 1974
Jan. 1, 1913
PARTICLE VELOCITY (mm/sec)
10^{-2}
10^{-3}
10^{-4}
10
100
DISTANCE (KILOMETERS)

Maximum "Induced" Earthquake, Clark Hill Reservoir Area.

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MAXIMUM "INDUCED" EARTHQUAKE

CLARK HILL RESERVOIR AREA

Consultant report

to the

SAVANNAH DISTRICT

U. S. ARMY CORPS OF ENGINEERS

SAVANNAH, GEORGIA

17 December 1976

by

Leland Timothy Long

Prepared at the request of Mr Earl Titcomb in accordance with Contract DACW21-76-C-0136

MAXIMUM "INDUCED" EARTHQUAKE

CLARK HILL RESERVOIR AREA

SUMMARY

The earthquakes of the Piedmont Province and the Clark Hill Reservoir Area (CHRA) share many distinctive characteristics and do not appear to satisfy conventional tectonic mechanisms involving observable faults. Consequently, an alternate explanation for the earthquake mechanism is proposed which involves stress amplification or strength modification in coherent near-surface geologic units. This mechanism allows a restriction on the size of the maximum plausable earthquake by placing practical limits on the size of the fault plane and magnitude of the stress drop. The upper limit in size for the fault plane is the 39.5 km^2 implied by microearthquake activity near Jocassee lake. CHRA microearthquakes and geologic units indicate about 10 km^2. The stress drop estimates for these events is consistantly about 6 bars. Using 6 bars and a fault plane of 39.5 km^2 in the relation of Randal (1973) a magnitude 5.6 event is the maximum plausable "induced" earthquake.

MAXIMUM "INDUCED" EARTHQUAKE

CLARK HILL RESERVOIR AREA

INTRODUCTION

Earthquakes in the Clark Hill Reservoir Area share many distinctive characteristics with earthquakes occurring throughout the Piedmont Province of Georgia and South Carolina. A typical event has a depth of focus less than 5.0 km as indicated by the generation of large surface waves and by aftershock studies. Their magnitudes have been less than $M_L = 5.5$ with the Union County earthquake of January 1, 1913 being the largest ($M_L = 5.45$). No coherent active faults have been identified as causitive structures connecting two or more Piedmont Province earthquakes. The earthquakes have occurred primarily as swarms or aftershock sequences in a limited number of discrete epicentral zones. The near-surface geologic units of the Piedmont Province are largely made up of metamorphosed sedimentary and volcanic rocks which have been penetrated by both mafic and granitic intrusives. The resulting complexity in geologic structures allows a significant heterogeniety in physical properties of the near surface rocks while also allowing highly competent rocks to occur within a few hundred feet of the surface. Because of these common characteristics, the earthquakes all probably share a common explanation which can be expressed in terms of the causitive stresses and the near-surface geologic structures.

The fundamental explanation for crustal stresses which cause earthquakes in the Piedmont Province is not currently understood completely, largely because of a lack of data. The conventional explanation of earthquakes in terms of continued movement along existing faults is not supported by existing

data. In order to explain the earthquakes in the Piedmont Province, Long (1976) proposed an alternate mechanism of stress amplification by shear modules inhomogenieties near the surface. In stress amplification, the geometry of anomalously rigid structures cause the amplification of applied or residual stress. To acheive stress large enough to cause earthquakes, first a structure with appropriate geometry must exist, second the structure must consist of a material with anomalously high rigidity and/or low strength and third a stress must be applied (or the strength changed) in a direction appropriate to cause stress amplification. The origin of the causitive stress is probably the result of a combination of factors. Because of the thickness of the Piedmont Crust (35 to 40 km) and the relatively smaller size of most near surface inhomogenieties (less than 5 km), crustal flexure probably contributes only slightly to the ambient stress field. Near-surface factors such as unloading through weathering, inhomogeneous stream erosion, and strength modification through weathering or fluid penetration, probably dominate as mechanisms for stress accumulation. With stress amplification or strength modification these could explain Piedmont Province earthquakes.

Some of the Piedmont earthquakes have occurred near reservoirs and their occurrence has been attributed to reservoir loading or fluid pressure effects (see Denman 1974, Talwani, 1976). However, with the exception, perhaps, of the Jocassee reservoir, earthquakes which are located within 10 km of the Blue Ridge Province, the larger events are not directly correlatable in time with the reservoir loading. Many areas which showed activity after loading, like the Clark Hill Reservoir or Lake Synclair, also had a history of seismic activity prior to loading. In the Clark Hill Reservoir area and other reservoirs spacially associated with earthquakes in the Piedmont Province, the earthquakes are not always located near the deepest part of the reservoir as they should be if they were purely reservoir induced. The marginally

convincing spacial and time correlation of large events with reservoirs suggests that the reservoir itself may not be responsible for the production of seismic activity through loading. However, the possibility cannot be ruled out that large lake fluctuations or rainfalls act as a catalyst when stress conditions reach levels suitable for the production of microearthquakes. Indeed, the near surface occurrence of events and the hypothesis given above concerning their cause would be compatible with water level fluctuations or rain falls acting as catalysts to microearthquake activity.

If the hypothesized mechanisms given above is assumed to be a correct and exclusive mechanism for Piedmont Province earthquakes, then the establishment of a maximum, plausible earthquake, induced or natural, is possible. The object of this study is to estimate the maximum plausible earthquake to be expected for the Clark Hill Reservoir Area given the mechanism presented above. The first step will be to estimate the largest possible fault plane and the type of movements that might occur. Next the stress drop will be estimated by comparison to similar sized events for which the stress drop has been measured. Stress drop estimates for Clark Hill Reservoir Area microearthquakes will be utilized in the evaluations. Finally, theoretical and observed relations between fault size and stress drop will be used to estimate the local magnitude of a maximum plausible earthquake.

ESTIMATE OF LARGEST PLAUSIBLE FAULT PLANE

Active faults, directly related to contemporary seismic activiety are not known for the Piedmont Province of Georgia and South Carolina. No coherent faults have been identified as causitive structures connecting two or more Piedmont Province earthquakes. Linear allignment of epicenters separated by distance equivalent to the source dimensions of the earthquake have not been observed and would be necessary to hypothesize a fault in the

case where a fault would not be observed at the surface. More typically, Piedmont Province earthquakes occur at discrete locations. These locations are separated by distances significantly larger than the dimensions of the earthquake source. Also, if more than one event occurs at one of these discrete locations, the epicenters are not distinguishable with existing teleseismic data. In a few individual earthquakes, the proximity of the epicenter to known faults has prompted speculation concerning the active status of the faults (Talwani, 1976). However, no evidence of recent movement can be observed on these faults and the seismic correlation is weak. All the faults represent movement at a time when the tectonic stresses were significantly different than they are today.

As a consequence of the lack of confirmed active faults, the problem of determining the maximum fault plane requires data from sources other than the geologic mapping of faults. Data on aftershocks of large events are sparse in the Piedmont Province but available for the CHRA and Jocassee lake. These can be used to obtain information on the size of the zone of high stress. The aftershock locations of the August 2, 1974 CHRA earthquakes (Bridges, 1975) indicate a zone of maximum width of 5 km with the majority occurring within a 2 km central zone. More recent data at Georgia Tech indicates that the zone of activity has essentially remained the same (figure 1.0) but the level of activity has decreased. Data on aftershock locations computed by Talwani (1976) indicate the same general distributions. The depth of focus range from near-surface (within 0.5 km) to a maximum depth of focus of 2.0 km (see figure 2.0). Most occurred within 0.5 km of 1.0 km. The area of microearthquake activity associated with the Jocassee area (Fogle et.al., 1976) is significantly larger. Over a period of 3 months the epicentral area grew from 4 km to 9 km in diameter while at the same time the overall activity level was decreasing. The maximum depth observed for

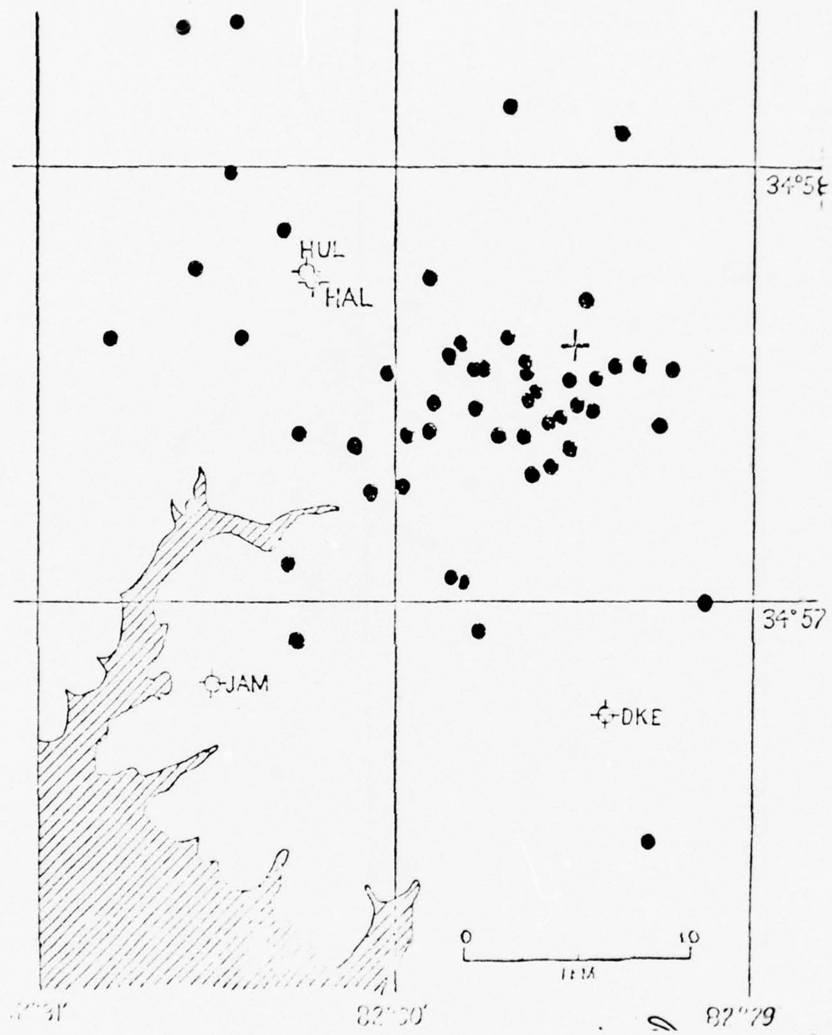

Figure 1. Epicenters for microearthquakes in the Clark Hill Reservoir Area.

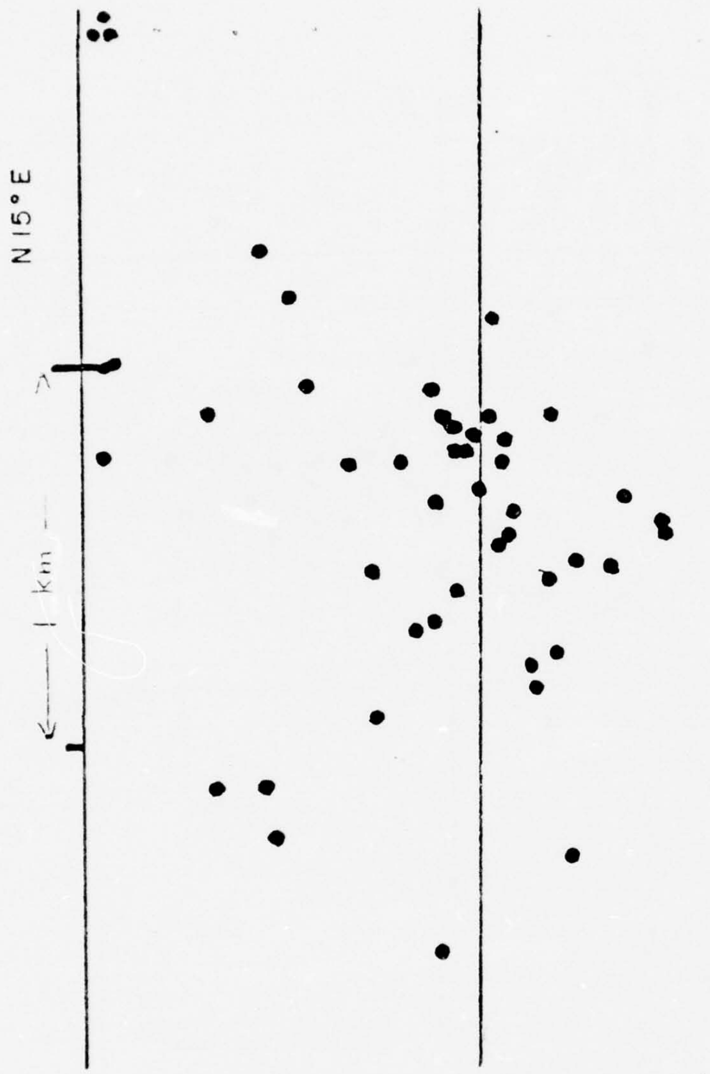

Figure 2. Cross section of hypocenters for events in the Clark Hill Reservoir Area. The hatch mark indicates the position of the cross in

aftershocks was about 4.0 km but significant activity was limited to less than 2.7 km deep.

The observed aftershock location for Piedmont Province earthquakes thus indicate fault planes of 10 km^2 for the CHRA and 39.5 km^2 for Jocassee after correcting for possible dip in the fault plane. There is an apparent discrepancy in the relative sizes of areas in that the largest event in the CHRA was a M_L = 4.8 while the largest event in the Jocassee area was a M_L = 3.2. However, in the Jocassee area the dominant active area at any one time was seldom wider than 2.0 to 3.0 kilometers indicating a lack of stress coherency throughout the area. Focal mechanism studies (Fogle et.al., 1976) indicate discrete epicentral zones of smaller size within the Jocassee area. In conclusion, the largest fault plane from aftershock distributions associated with a discrete event is 10 km^2 in the CHRA and for a composite epicentral zone is 39.5 km^2 in the Jocassee area.

An alternative approach to the determination of the maximum fault plane would be to evaluate dimensions of geologic units potentially related to the seismic activity. In both areas the aftershocks occur generally throughout a volume. At Jocassee, they occur in the Henderson Gneiss above the extrapolated position of the Brevard zone. In the CHRA they occur generally in a mixed gneiss unit corresponding to a negative Bouger anomaly. Hence, by assuming the fault plane to be limited by the dimensions of coherent geologic units an estimate of the largest plausible fault plane can be obtained directly from geologic structures. In the CHRA interpretation of gravity data (Long, et al., 1976) and the Geologic Map of Georgia (1976) indicate geologic units with widths typically less than 6 km with the exception of the Danburg Granite and the Lincolnton metadacite. The Lincolton metadacite however, is probably no thicker than 5 km. Most coherent geologic units are significantly less than 6 km. If these units have effective depths of less than 5.0 km then the largest plausible fault plane areas are about 30 km^2 or still less than the

39.5 km^2 for the Jocassee aftershock zone. The 5.0 km maximum depth estimate exceeds depths computed for any aftershock observed in the Piedmont Province. If a relation between these events and surface water loading exists then the depth of the maximum fault plane may be limited by the porosity of the rocks or the ability of existing joints to allow penetration to depth.

ESTIMATE OF STRESS DROP

The average stress drop along a particular fault plane in material with a given seismic velocity is a measure of the magnitude of the earthquake that will be produced. A high stress drop will give a larger earthquake than will a small or partial stress drop. Hence, the determination of plausible stress drops is an important factor in determining the largest magnitude event that a given fault plane can generate. The seismic velocities are also important because they define the rigidity and with the displacement the stress of the rock near the fault plane. The higher the rigidity, the smaller the displacement for a constant stress drop and fault dimension. The near-surface rocks in the CHRA have p-wave velocities on the order of 5.8 to 6.1 km/sec. These velocities are typical of rocks in the upper 10 km of the crust, below the superficial sedimentary rocks and imply that CHRA displacements computed for events of similar stress drop will be equal to or less than displacements computed for other shallow earthquakes. They also imply conversely that for the same displacement, the stress drops in the CHRA should be greater than or equal to stress drops in other shallow earthquakes. Unfortunately, data or measurement methods to directly determine stress conditions in the crust are not currently available. However, plausible stress drops can be estimated from in situ stress measurements, evaluations of stress drop for continental earthquakes, and computation of stress drops for Piedmont Province or CHRA earthquakes.

In situ stress measurement are not available in the CHRA. Nevertheless, measurements near Atlanta and the Bad Creek site near Jocassee indicate deviatory stresses on the order of hundreds of bars. At shallow depths, 1000 to 2000 bars is significant to cause rupture of fresh rock but it is unlikely that such stresses could exist over an entire fault plane. As indicated by the near-surface measurements, such stresses could exist at locked points along a fault plane or at discontinuities in a fracture surface. However, at distance the seismic waves of an earthquake are primarily determined by averages or effective stress drops distributed over the entire fault plane. Consequently, individual measurements of stress would not be expected to be as meaningful a measure of the average stress drop as would be stress drop estimates based on seismic waves at distance.

Evaluations of stress drops for intraplate earthquakes are limited. The most extensive available evaluation of eastern United States earthquakes (Street et al., 1976) indicated that events of seismic moment greater than 5×10^{23} dyne cm (equivalent to $M_L \geq 4.0$) have a stress drop of 6 bars. The lack of variation is indicative of a similar physical mechanism for the initiation of rupture along a fault. Street et al. (1976) also noted that the spectra from the larger events implied partial stress drop while the smaller events often implied complete stress drop. In commenting on the constant stress drop for large events, Street et al. (1976) suggested that the earthquake process in the region is uniform in contrast to southern California, where a wide range in stress drops occur for events with the same seismic moment.

The stress drop of the August 2, 1974 CHRA earthquake was evaluated by Bridges (1975). He used a variety of theoretical and empirical relations and observed data. The most reliable estimates averaged 5.0 bars and varied by only $\pm$ 1.0 bar. The theoretical estimates are based on the magnitude (M_L)

and fault areas estimated from the spectra and from the aftershock zone. The empirical methods (from Gibowicz, 1973) are based on aftershock "b" values and the difference in magnitude between the main shock and the largest aftershock. The normal stress drop (after Gibowicz, 1973) for a magnitude 4.8 event was given as 0.74 bars indicating that the stress drop for the CHRA earthquake of August 2, 1974 was anomalously high. The high stress drop is consistent with the implications of the high near-surface rigidity of the Piedmont Province, the lack of observed movement along existing faults and the mechanism of stress amplification in near surface geologic units.

Recent spectral data from the CHRA (Marion, 1977) indicates that the largest stress drop for microearthquakes was 7 bars. Furthermore, the spectra indicate transsonic rupture velocities and, consequently, a minimal frictional stress along the fault plane. These characteristics are indicative of a near-tensional stress condition which would be susceptable to perturbation by ground water pressure variations.

Plausible stress drop based on these date would be 5 to 7 bars. The data are remarkably consistent and no data in the Piedmont Province exists to indicate that higher stress drops exists.

LOCAL MAGNITUDE (M_L) FOR MAXIMUM EARTHQUAKE

In a consideration of the spectral theory of seismic sources and a comparison of the theory to spectral data, Randal (1973) developed a relation between Local Magnitude (M_L) fault dimension and stress drop. The relation was shown to be consistant for a large range of observed data. Figure 3 shows this relation modified for the generally observed stress drop of eastern United States and the Piedmont Province of 6 bars. The maximum fault planes

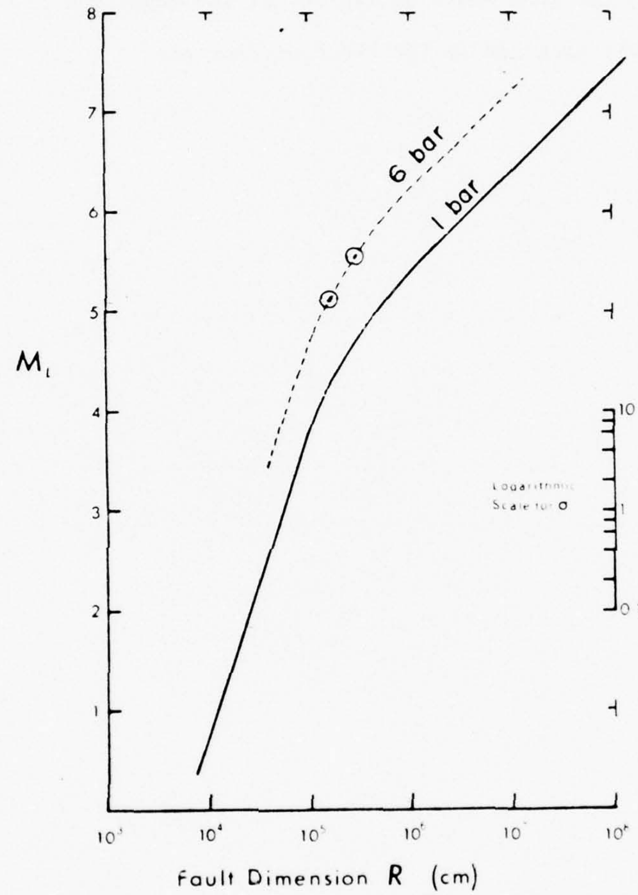

Figure 3. Randal's (1973) relations between local magnitude and effective fault radius adapted for a stress drop of 6 bars.

of 10 km^2 and 39.5 km^2 indicate maximum events of magnitude (M_L) 5.1 and 5.6 respectfully. The largest magnitude observed for a Piedmont Province earthquake is 5.45 (Long, 1977) and is consistant with the maximum plausible earthquake computed independently from stress drop considerations and plausible fault plane dimensions. The smaller dimensions indicated by individual activity zones in Jocassee area and by the geologic units prevalent in the CHRA would be typical of the magnitude 3.0 to 4.5 events more commonly observed in the Piedmont Province.

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Section D

A Seismic Risk Analysis of the
R.B. Russell Dam Site

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A Seismic Risk Analysis
of the R. B. Russell Dam Site

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Cambridge, Massachusetts
February 1977

SUMMARY

Using U.S. Army Corps of Engineers input assumptions, this seismic risk analysis produces estimates of M.M. Intensity V and VI as the intensities associated with 0.01 and 0.003 annual risks respectively. Translation to peak ground accelerations can be accomplished in several ways, typically giving 0.01 annual risk acceleration values (100-year return periods) of about 0.075g. Lower risk values are more sensitive to the translation technique and the input.

INTRODUCTION

The objective has been to estimate the annual probabilities of exceeding any given level of earthquake intensity* at the R. B. Russell Dam Site. The estimates are based on analytical seismic risk analysis utilizing parameter values and data provided by the U.S. Army Corps of Engineers (USACE). The primary task was to estimate these risks (1) in terms of the Modified Mercalli (M.M.) Intensity at the site and (2) with the parameter values directly provided. This study is presented in Part I of this report. A secondary task has been to estimate these risks (1) in terms of peak ground

*The term "intensity" is general and includes peak ground acceleration; the capitalized word "Intensity" refers to the Modified Mercalli (M.M.) scale specifically. Both Roman and Arabic numerals will be used for M.M. Intensity.

accelerations at the site and (2) with consideration of additional or alternative parameter assumptions. This study is outlined in Part 2 of this report.

PART 1: MODIFIED MERCALLI INTENSITY RISKS FROM USACE INPUT

Objective The output of this analysis is a plot of annual probability of exceeding (or its reciprocal, mean annual return period) versus M.M. Intensity experienced at the R. B. Russell Dam site. The input includes estimates of potential epicenters of earthquakes, their epicentral M.M. Intensities, the mean annual (and relative) occurrence rates of the latter, plus attenuation laws that predict site Intensity given epicentral Intensity and distance. The information used for the input is that provided directly by the U.S. Army Corps of Engineers, with interpretation by the consultant where necessary. The reference for this information is the handout material of the November 18, 1976, meeting on the R. B. Russell Project at Vicksburg, Mississippi, plus associated discussion periods. This material included source zone maps, an earthquake catalogue, and attenuation equations, etc.

Input; Source Zones The source zones are those identified by the names Piedmont, Blue Ridge, Coastal Plain, and Charleston Area on a USACE map entitled "Seismic Zonation Around Project Site" in the handout material cited above. The map is reproduced as Figure 1 here. Bounding the region by the latitudes and longitudes shown (and eliminating the area represented by the M.M. Intensity Scale information block in the lower left corner of the map), the areas of the four regions are estimated to be about 123,000 km^2, 49,500 km^2, 69,000 km^2, and "zero" km^2, respectively. Becuase of its dis-

tance of several hundred kilometers, the Charleston region can be satisfactorily (and more simply) represented as a concentrated "point" source of activity (hence, its zero area).

Input; Source Activity Rates and b-Values These parameters were estimated by the consultant from the catalogue of earthquakes provided by the USACE. The object was (1) to estimate ν, the mean number of events per year greater than epicentral M.M. Intensity V in each of the four sources and (2) the b (or slope value) in the standard log $N_{I_-} = a - bI_0$ relationship (in which N is the mean annual number of events equal to or greater than intensity I_0). The value M.M. Intensity V is used simply as a convenient reference value. (Smaller values are in fact included in the computations, but they are not significant.) The important sources are the Piedmont and Charleston. As will be confirmed in the results, errors in estimating ν and b for the other two sources are not important because of the combined large minimum distance and low maximum M.M. epicentral Intensity potential of the Blue Ridge and Coastal Plain sources.

Simple catalogue counts in 119 years (1857-1976) revealed 15 events of V or greater* in the Piedmont source zone (Fig. 1) and 8 such events near Charleston. There were 4 events in each of the other sources. These values produced ν values of 0.126, 0.0336, 0.0336, and 0.0672 for the 4 sources respectively.

The values of b were estimated from log N versus I_0 plots of the data. For the Piedmont a line was fit through the Intensity V and VI values (assuming that some values of IV or less are unreported and that the value at VII is statistically unreliable, being based on a single event). This line

*All borderline values, e.g., those denoted IV-V in the catalogue, were counted (conservatively) as the larger value.

yields a b value of 0.36. (As will be discussed in Part 2, this value is probably low; low values are conservative as they imply larger numbers of larger events.) Data were insufficient to estimate the b values in the Blue Ridge and Coastal sources (e.g., there were no VI's or greater). Therefore, the same value, b = 0.36 was used. For the Charleston source, a value of b = 0.31 produces a line which passes almost perfectly through the values at Intensitiy IV, V, and VI.

Input; Upper Bound Epicentral Intensities These values were obtained from the upper bound magnitude values provided by the USACE reference. They were M_L = 5.5, 5.5, 5.0, and 7.0 for the Piedmont, Blue Ridge, Coastal, and Charleston sources respectively. Using $M_L = 2.1 + 0.5\ I_o$ (from the referenced USACE material), one obtains maximum epicentral intensity values of VII, VII, VI, and X for the 4 sources. The USACE and their consultants confirmed these Intensity values.

Input; Attenuation Laws The attenuation laws recommended by USACE were

$$I = 4.75 + 1.25\ I_o - 5\log_{10}D \qquad 10\ \text{km} \leq D \leq 100\ \text{km} \qquad (1)$$

$$I = 3.7 + I_o - 0.0011D - 2.7\log_{10}D \qquad D \gtrsim 100\ \text{km} \qquad (2)$$

in which D is the epicentral distance. For very small values of D, $I = I_o$, of course. The first equation above produces a discontinuity at D = 10 km if used with $I = I_o$ for $D \leq 10$ km. This was eliminated by using:

(a) $I = I_o$ for $D \leq 20$ km for $6.0 < I_o \leq 7.0$

(b) $I = I_o$ for $D \leq 16.5$ km for $5.0 < I_o \leq 6.0$

(c) $I = I_o$ for $D \leq 10$ km for $I_o \leq 5.0$

together with the first equation above for values of D larger than those indicated here (but less than 100 km).

The dispersions ("Standard errors") in the attenuation prediction equations were not provided directly by the USACE. The consultant estimated these from the USACE provided figure entitled "Intensity Attenuation Versus Epicentral Distance in the Region of Richard B. Russell Dam." Those historically observed values of site Intensities were plotted versus the I (versus I_o and D)predictions from the equations shown above, and the errors (observed minus predicted values) noted. For the "far-field" attenuation law (Eq. 2), the average error was only 0.04 (i.e., the prediction is effectively unbiased) and the standard deviation (or "standard error") was found to be 0.50. (The sample size was 13.) For the "near-field" equation (Eq. 2), the average error was -0.99, suggesting an unconservative bias (the sample size is only 9, however). The standard deviation (which is based on the mean squared value with respect to the average observed error, not with respect to the predicted value) was 0.77.

Analysis Method The analysis method used is that referred to.as seismic risk analysis (see, for example, Cornell and Merz, Journal of the Structural Division, Proc. ASCE, Vol. 101, No. ST10, 1975, p. 2027, and references therein). It integrates over possible epicentral intensity values, possible epicentral locations, and possible deviations from the attenuation prediction (all with their appropriate relative frequencies) to determine the risk that a given M.M. Intensity is equalled or exceeded at the site in any year.

Results The results are shown in Figure 2 as a curve marked "Total Risk." The estimated risk for site M.M. Intensity V is 0.01 (i.e., M.M. Intensity

V is the value with a 100-year mean return period). Intensity VI has a computed annual probability of being exceeded of about 3×10^{-3} (i.e., a 350-year mean return period). The model predicts non-zero risks of intensities greater than the local epicentral upper bound of VII, because of the dispersion in the attenuation law; for example, an epicentral event of 7.0* (outside the 20 km epicentral region, at least) may have an estimated site intensity of say 6.75, but there is about a 1/6 chance of an "error" of 0.77 units (the value of the standard deviation) or more, i.e., a site intensity of about 7.5. These observed deviations from the predicted site intensity (especially those that produce values larger than the epicentral value) may be attributed in part to poor local soils conditions at the site where the higher-than-predicted intensity was originally observed. If the dam is built on good foundation materials, such large deviations may well not occur at its site. In short, in application to the Russell dam site, the risks estimated here are conservative with respect to the deviation assumption.

Of significant interest are the relative values of the contributions to the total risk. As shown in Figure 2, with these parameter values, the Charleston source contributes the major portion of the risk over the entire intensity range. Virtually all the remainder of the risk is contributed by the Piedmont source. For example, at site Intensity V, where the total risk is 0.010, the contribution from the Charleston source is 58% and the contribution from the Piedmont source is 28%. Of this total of 28%, about 12% is from events of epicentral intensities of 6.0 or less, while the other 16% is from Piedmont events of 6.0 or less. Of the 28%, about 11% is from events occurring so close that the site lies within the epicentral

*The program treats M.M. Intensities on a continuous scale; hence, the use of decimal values. If this disturbs the reader, consider these "M.M. Intensities" as re-scaled Magnitudes (or in the site intensity case as re-scaled log accelerations).

(i.e., within the maximum iso-seismal line), whereas the other 17% is caused by events occurring at a greater distance. The larger Charleston risk contribution is not surprising; consider this simplified calculation. For attenuation law given above (Eq. 2), it requires an epicentral Intensity of 8.2 or greater to cause at site intensity of 5.0 or greater (assuming the prediction error term is zero). But the mean annual rate of such events at Charleston is $0.067 \times 10^{-0.31(8.2-5.0)}$ or 0.007. This is 70% of the total risk of 0.010 of site intensity 5.0 or more.

PART 2: PEAK GROUND ACCELERATION RISKS

In this part of the report we shall consider the annual risks of exceeding a specified peak ground acceleration, a, at the site. In addition several components of the analysis and parameter values used above are discussed more fully. Several alternative sets of results are presented.

Estimated Peak Ground Acceleration Risks/USACE Input One technique that can be used to estimate the peak ground acceleration from a given M.M. Intensity (associated with a particular annual risk) is to use a simple I to a conversion. The USACE handout material referenced above makes use of an unpublished document entitled "Design Earthquakes," by E. L. Krinitzsky and F. K. Chang of the USACE Waterways Experiment Station. They give plots of accelerations corresponding to a given M.M. Intensity in the near and far field and for different likelihoods of being not exceeded. The "predicted values" (i.e., the median values or the values with a 50% probability of not being exceeded) of peak ground accelerations given M.M. Intensities V and VII are, respectively, 0.05g and 0.20g in the near field and about 0.02g and 0.12g respectively in the far field. These results are not inconsistent with those estimated by several others in recent years. The near-field predictions are much larger, however, than the earlier Gutenberg-Richter relationship commonly used.

These median values might be used to transform the Total Risks results of Figure 2 to give peak accelerations corresponding to given annual risks. Presumably, because of the large risk contribution due to Charleston, the far-field transformation is to be preferred*. This implies a 100-year mean

*Weighted schemes could also be developed.

return period of about 0.02g and 2500-year return period for 0.12g.

However, the dispersion in the I to a relationship is large. The aforementioned Krinitzsky and Chang paper shows a 85% fractile of 0.38g for I = 5 and 0.6g for I = 7 in the near-field,and 0.09g and 0.2g, respectively, in the far field. The implication is that it is not unlikely that very small M.M. Intensities produce ground accelerations larger than those predicted (expected) from only much higher M.M. Intensities. For example, with these results an M.M. Intensity of only IV to V has a 15% chance of producing an a value of 0.2, which is a value not expected until an M.M. Intensity VII. The (near-field) dispersion implied by the USACE paper cited is substantially greater than that estimated by others. The typical 3-1/2 to 1 ratio of the 85% fractile to the median (near-field) is often reported as about 2 to 2-1/2 to 1 by other data analysts. It must be granted that virtually all other analysts have mixed near- and far-field data. Krinitzsky and Chang find a ratio of somewhat less than 2 for this ratio in the far field. Their near-field dispersion value is probably much too conservative, however.

Instead of using median relationships, the risk curves could be translated from M.M. Intensity to peak acceleration via "conservative" translations such as the USACE 85% fractile levels. Using the near-field translation, this produces a 100-year return period acceleration of more than 0.3g (M.M. Intensity V). But this result is incorrect because the risk analyses imply a large contribution from the Charleston source for which a far-field translation is more appropriate. Using the USACE 85% fractile far-field conversion, one obtains a 100-year return period acceleration of about 0.08g and 0.2g for the 2500-year value.

In principle, the translation should be found by considering (integrating over) all possible conversion factors together with their relative likelihoods. (See, for example, the Cornell and Merz reference cited above.) The same result is produced, however, by re-doing the seismic risk analysis for $Ln_e(a)$. This is accomplished by inserting a (median-value) relationship such as $Ln_e(a) = b_0 + b_1 I$ into Equation 1 and 2 and by properly combining the standard deviation of I (given I_0 and D) with that of a (given I). Assuming that a given I is approximately lognormally distributed (as several investigators have found), the natural log of the ratio of the 84% fractile to the 50% fractile can be interpreted as the standard deviation of $Ln_e(a)$ given I. In the near field the USACE value is 1.25 and in the far-field about 0.59. The rule for combining these standard deviations with those cited for the attenuation laws is simply the square root of the sums of squares* (after first multiplying the standard deviation of I given I_0 and D by b_1 from the relationship $Ln_e(a) = b_0 + b_1 I$; this b_1 value is about 0.8 for a up to 0.2 (I up to VII) and about 0.46 for larger values). The (too large) term associated with the standard deviation of the I to a transformation dominates the total result of $\sigma_{Ln(a)} = 1.60$, for near-field, smaller a levels; $\sigma_{Ln(a)} = 1.38$ for near-field, larger a levels; and $\sigma_{Ln(a)} = 0.65$ for all far-field values. The results of this analysis are a 100-year return period for 0.07g and a 350-year return period for 0.2g.

Notice that the return period of a 0.2g site acceleration is substantially less (the risk higher) than that predicted even by the conservative, far field simplified I to a translation. Detailed inspection of the results shows that Charleston no longer contributes significantly to the risk at this acceleration level; the risk of exceeding a 0.2g is now due almost solely to near-field smaller (M.M. Intensity) events. The reason is the difference

*Recent, unpublished results have found also a small negative correlation which is conservatively neglected here.

in the near-field versus far-field acceleration predictions and the above-stated high likelihood of smaller M.M. Intensity (near-field) events causing much higher-than-expected accelerations.

Discussion of USACE Input Values The consultant believes that several points concerning the recommended input values used above deserve a critical review by the USACE and its other consultants.

The catalogue alone may not produce as reliable estimates of mean occurrence rates, ν, and b-values as a broader look at East Coast regional seismicity might. Incomplete recording of Intensity V events in the Piedmont region considered may explain why the b value (0.36) is unusually low. Bollinger (B.S.S.A., Vol. 63, No. 5, 1973, p. 1785) estimates a b value of 0.59 for the Southeastern U.S.* This may well be a preferred b value. Used in conjunction with the assumption that the counting of M.M. epicentral Intensity VI's or higher has been complete in the Piedmont source (i.e., 7 in number), we extrapolate backwards to an estimated 28 events of V or more. This yields a ν value of 0.235 (rather than 0.126) per year. The net effect on the risks of changing both b and ν will not be large, however. It will generally reduce the risks of larger intensities.

The attenuation laws (Eqs. 2 and 3) have marked discontinuities at 100 km that preferably should be resolved. More importantly, the observed unconservative bias in Eq. 1 deserves more careful study. As mentioned, based on 9 data points (within 100 km), it predicts on the average about 1 M.M. Intensity unit too low. This possible bias may be less at smaller (more important) distances (recall that the lower value of D was adjusted so that it predicts $I = I_0$ at $D = 20$ km or less).

The M.M. Intensity to acceleration translations also deserve more careful study. They are the source of very large accelerations (for given near-

*In an earlier paper, Bollinger also found a Charleston b value of 0.31 and pointed it out as an anomoly.

field M.M. I values). The recent work of R. K. McGuire at USGS may be relevant. In particular, the large dispersion in the Krinitzsky/Chang relationship (together with the unusually low slope b_1 at moderate-to-high M.M. I values) implies that substantial risks of very high a values are unrealistically and conservatively being attributed to only moderate M.M. Intensity values. Roughly, the risk for a given source is proportional to $e^{1.15\sigma^2/c_2^2}$ in which c_2 is the constant in I (or $\ln_e(a)$) = $c_1 + c_2I_o - c_3\ell nD$. For the near field, c_2 is 1.25 for I; it is about 1.0 for $\ln_e(a)$ (for a less than about 0.25g) and about 0.6 for higher values of a. The exponential dependence implies risks very sensitive to high σ values, especially if c_2 is low and b large. See below.

The consultant considered several alternative parameter choices. For example, without adjusting the possible bias in the attenuation law, the other parameters were altered to personally preferred values. The ν and b values for the Piedmont were adjusted to those just discussed. The standard deviation of the near-field I-to-a transformation was reduced from 1.25 to 0.8 yielding a net value of about 1.3 (rather than 1.6) for smaller a values (less about 0.2g) and 1.0 (rather than 1.38) for larger a values. The results are a 0.01 annual risk (100-year mean return period) peak ground acceleration of about 0.07 and 0.08g; a 0.0014 annual risk (700-year) acceleration of about 0.2g. These acceleration values are comparable to those above for larger risks, but substantially smaller for annual risks of 10^{-3} or less. Given an M.M. Intensity no greater than VII, however, even these higher acceleration peaks (above 0.2g) would be associated with very short durations.

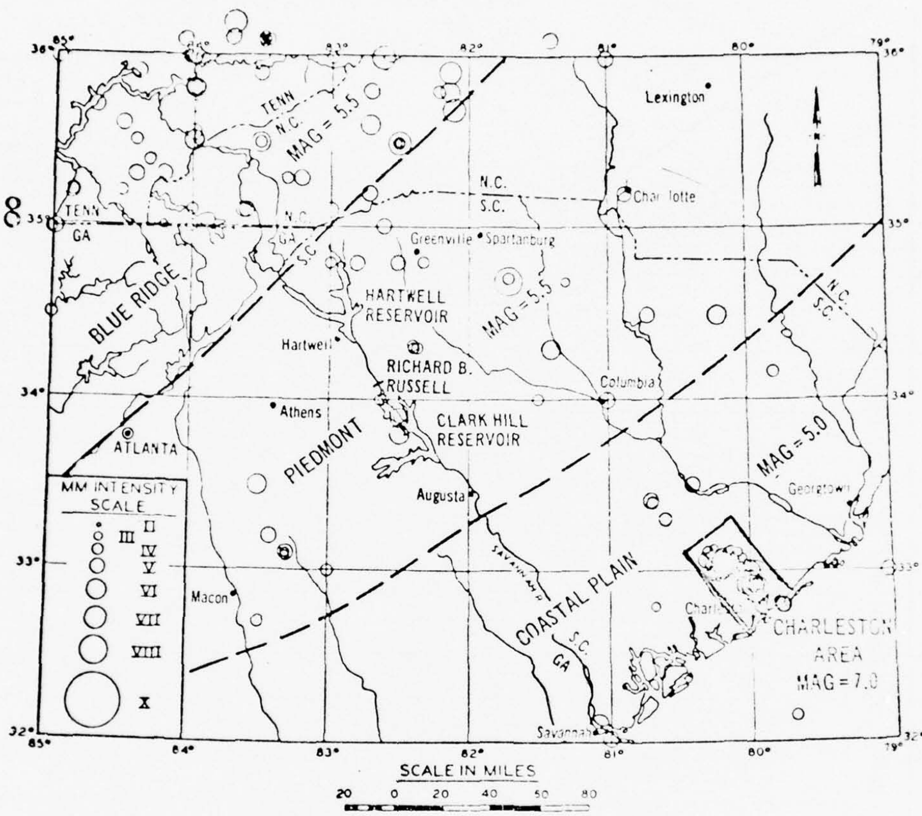

Fig. 1 SEISMIC ZONATION AROUND PROJECT SITE

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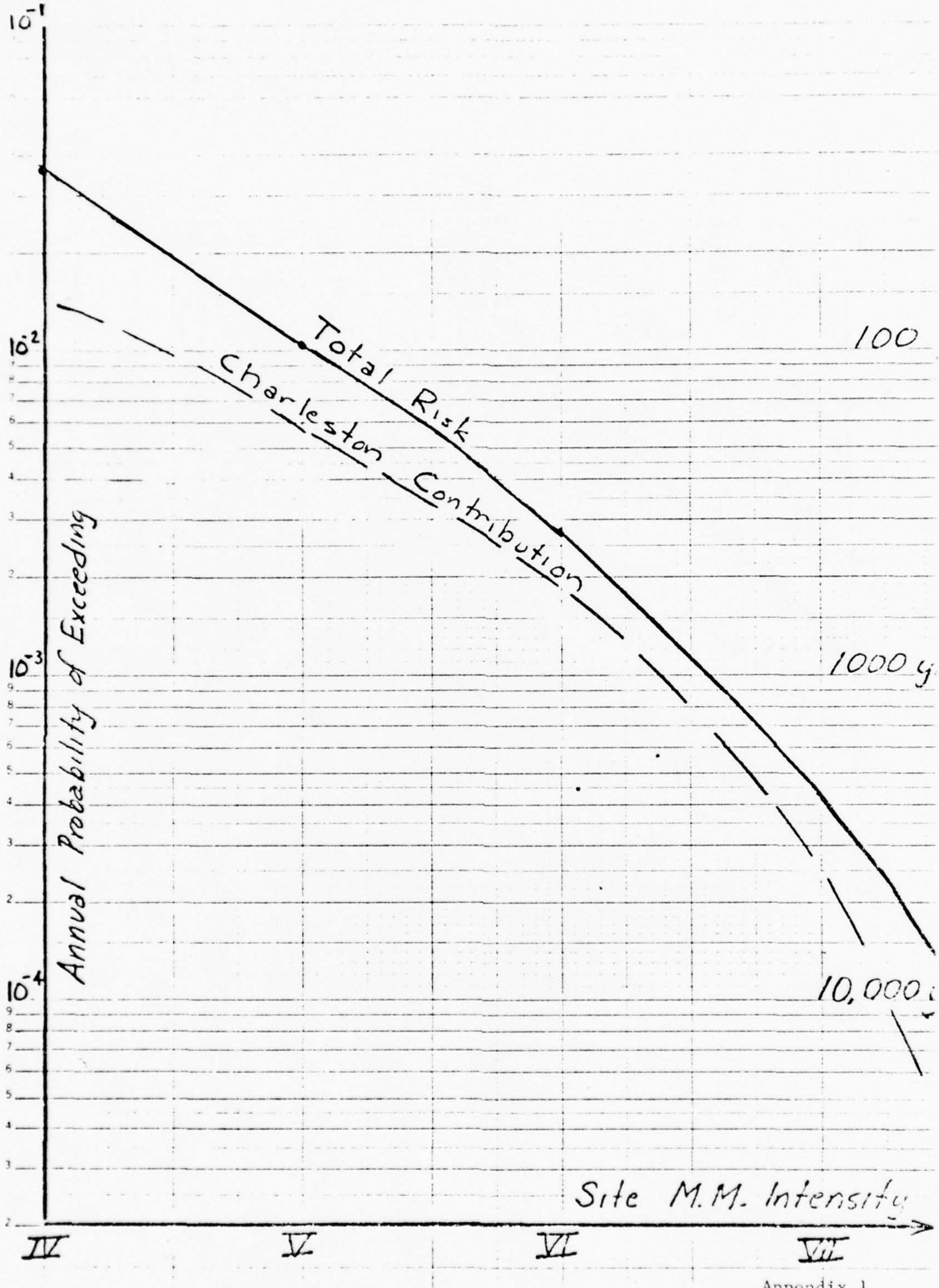

Fig. 2 Intensity vs. Annual Risk

SECTION E

INDUCED SEISMICITY AT

RICHARD B. RUSSELL RESERVOIR

BY

DAVID T. SNOW

INDUCED SEISMICITY AT RICHARD B. RUSSELL RESERVOIR

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INTRODUCTION

It is appropriate to investigate the setting of a new lake, such as the Richard B. Russell Reservoir, to ascertain whether or not special circumstances exist that should be included in a prudent evaluation of seismic risk. As will be shown, a rational prediction may be made of induced seismicity or aseismicity, but the state of the art does not offer proof that a site having unfavorable conditions will necessarily show enhanced seismicity. This report details the findings of such a study, conducted during July to December, 1976. It entails both library and field research, and integrates into the problem some aspects of the structural geology, geomorphology, hydrogeology and rock mechanics.

Evaluation of the potential for induced seismicity by a proposed reservoir may follow either an empirical line of comparison with other reservoirs, regions or circumstances, or alternatively, it may develop a rational theory of cause and effect. Neither suffices alone, and even in the best combination, these two approaches do not yield answers as precise as we need. Because a set of circumstances both necessary and sufficient to produce earthquakes by reservoir loading is not yet known, the empirical approach is minimized in this report, in favor of a genetic, causative approach that may lead to better understanding of the phenomenon, more reliable prediction, and theory applicable in other geological circumstances.

A brief summary of seismological and geological circumstances follows. These topics are dealt with in depth by Krinitzsky, Lutton and Hancock in this volume. Because the empirical comparison is largely inconclusive for prediction in this case, subsequent sub-

headings of this report develop background for interpreting the history of local stresses. Upon this sequence of stress changes will be superimposed the stresses to be developed by the reservoir, the last event. In this way, a criterion of prediction of induced seismicity will be developed for the Richard B. Russell Reservoir.

SUMMARY OF SEISMOLOGIC AND GEOLOGIC CIRCUMSTANCES

There have been a few reservoirs in the world that have shown a strong relationship in time and space to significant earthquake incidence. Among these are Kariba in East Africa, Koyna in India, Kremasta in Greece (Snow, 1973, 1974, 1972), Bileča in Yugoslavia and Hsinfengkiang in China (National Academy of Sciences, 1972). There is a much longer list of less certain reservoirs (approaching 30) associated with earthquakes of lower intensity or that die out soon after filling (Simpson, 1975). Among these are several in the Piedmont Province of southeastern U.S. (Severy, et. al., 1975), wherein the proposed Richard B. Russell Reservoir is to be situated. Clark Hill Reservoir, immediately downstream on the Savannah River, is one that has conceivably stimulated quakes (Talwani, 1976). Jocassee Reservoir, 97 miles upstream on the Keowee River, has been associated with many low-intensity quakes (Talwani, personal communication, 1976). The geometrical distribution of Jocassee quakes around and under the reservoir and its timing soon after filling present a more convincing relationship than does the localized swarm near McCormick, South Carolina, 22 years after filling of the Clark Hill Reservoir. Hartwell Reservoir, immediately upstream of the proposed Russell Lake, and Keowee next upstream, have not been identified with more than one event each. Those reservoirs located nearby the Richard B. Russell site offer the best possible tests of the induced seismicity to be expected upon filling. No special circumstances of each reservoir have been discovered that would indicate plausible reasons why some (Hartwell and Keowee) should be

evidently aseismic, another (Clark Hill) weakly seismic or delayed in response, and the third (Jocassee) is producing swarms of low magnitude ($M<4$) quakes. Jocassee may be too distant for comparison.

Severy, et. al. (1975) have summarized seismic circumstances of 60 Piedmont reservoirs from Pennsylvania to Alabama. At 11 of them, one or more earthquakes have occurred nearby since filling, but they were all in areas of natural, historical seismicity. The larger and deeper reservoirs have had more nearby quakes than have the lesser reservoirs. Unlike most seismic reservoirs of the world, however, most of the Piedmont occurrences were many years after filling. Only Jocassee and Clark Hill have had more than one reported nearby quake. This is not simply a consequence of instrumentation, because Carter's Lake, Georgia, and Lake Anna, Virginia, have proven aseismic with arrays of sensitive seismographs installed (L. T. Long, personal communication, and Severy, et. al., 1975). Only the Jocassee swarm follows closely the typical prompt response to filling of a seismic reservoir.

Hadley and Devine (1974) summarized the regional seismic and structural contrasts of the eastern provinces. More detailed seismicity of the locality is found in Long (1974) and Talwani (1975). The greatest nearby events experienced have been the $M_L=4.3$ quakes of August 2, 1974, near Clark Hill Reservoir and the $M = 2.8$ and 3.0 quakes of October 17, 1975, and February 4, 1976, near Jocassee. Similar shaking could have occurred without reservoir stimulation, since the Lincolnton, Georgia, quake of November 1, 1875, and the

Union County, S.C., quake of January 1, 1913, were more intense than the 1974 events.

If all the necessary tectonic circumstances are met at a reservoir site, and if the stress changes are demonstrably unfavorable, then reservoir impounding can be expected to increase seismicity by (1) causing seismic events and swarms to occur sooner than natural processes would dictate, and (2) causing events to take place closer to the reservoir than otherwise. Unfortunately, we do not really know what all the necessary circumstances are. It is debatable whether a seismic reservoir may produce greater intensity quakes than would be predictable from the statistics of past events, natural and induced. Of all the alleged seismic reservoirs of the world, only Koyna has produced a quake greater than had previously been experienced in its region (Snow, 1974).

The dam is to be founded on foliated meta-dacite of the Charlotte Belt, and the reservoir extends, dendritic in form, northwesterly across the strike of foliation onto schists and high-grade gneiss units. There are numerous steep, east-dipping shear zones, among them the Loundsville Belt, that cross the proposed reservoir. The detailed dam-site geology is described in the project design memoranda, and the pertinent literature on the areal geology are summarized by R. T. Lutton and W. Hancock in this volume (see bibliography). From the standpoint of induced seismicity, the significant features are topographical, hydrological and mechanical:

(1) The reservoir has moderate slopes and a dendritic pattern

without a significant basin. Erosion has removed a calculated 38% of the slab encompassed by the watershed area, taken to a depth equal to the relief, about 270 feet. The volumes were computed from the stage-area and stage-capacity curves given in Figure 1. These have been formed by planimetering contours above the reservoir, extending the Trotters Shoals lower site data of 1968. (2) The jointed, faulted, steeply foliated intermediate to high-grade metamorphics have permeability that can be expected to assure deep penetration of pore-pressure effects to hypocentral depths of several km. Permeability is probably greater parallel to the foliation than across it. Such anisotropy, with maximum across the reservoir's long axis, suggests propagation of reservoir pressures far along strike and to great depth, where average potential effects may approximate half the surface effects. These features are discussed in a sub-heading on hydrogeology. (3) Whereas the basement rocks are covered with as much as 120 feet of saprolite on hills and slopes, the rock is hard and brittle to great depths, of the quality exposed along the Savannah River. Persistence of sheared material and voids in numerous deformable inclined fractures indicates that lateral stress changes in response to vertical changes should be computed on the basis of a Poisson's ratio of about 0.3, higher than laboratory data on intact cores would suggest. In addition to shears parallel to steep SE-dipping contacts there are fractures trending NW and NE that locally control stream courses.

The state of ground stress varies with depth and position

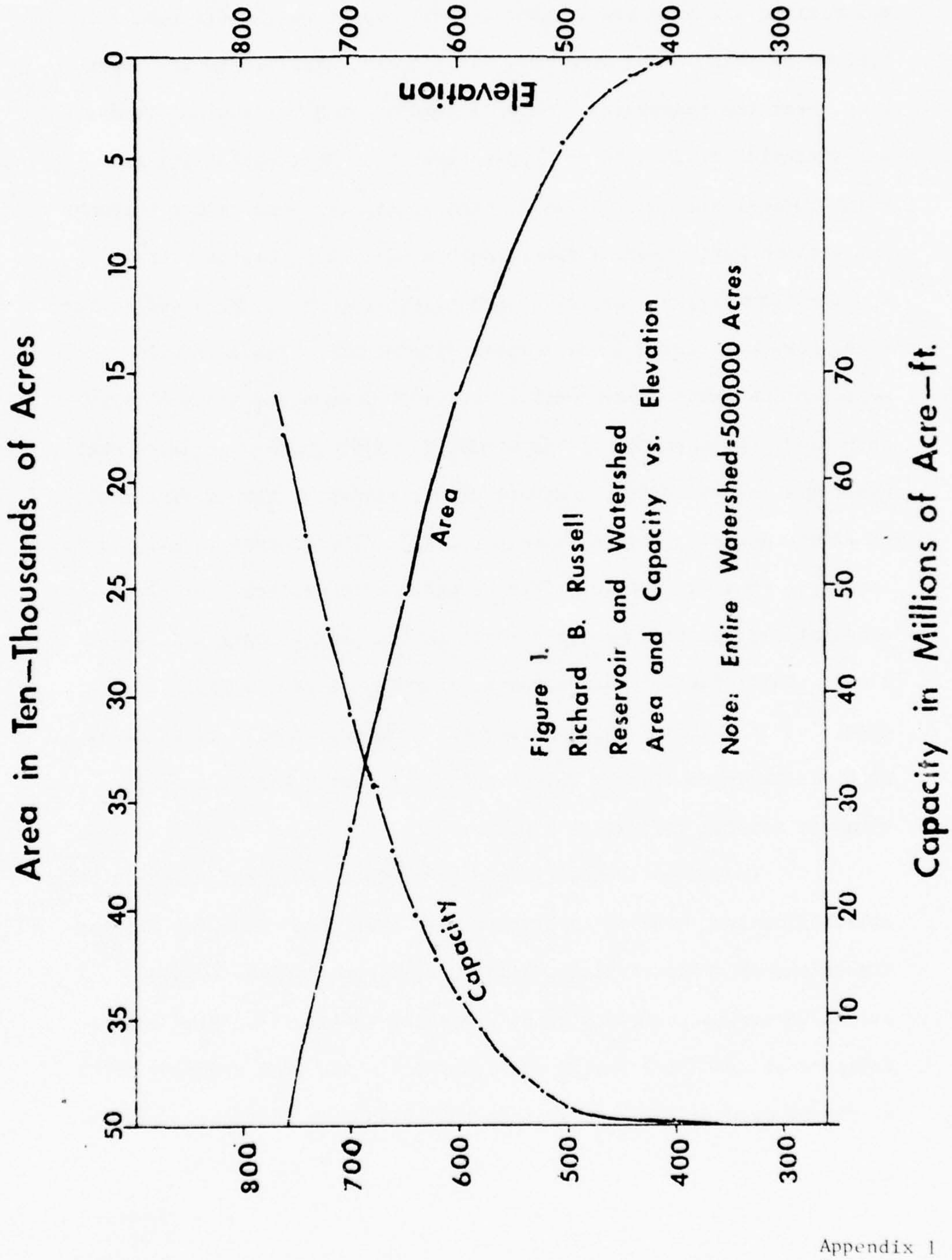

Figure 1.
Richard B. Russell
Reservoir and Watershed
Area and Capacity vs. Elevation

Note: Entire Watershed=500,000 Acres

relative to topography, but since there is a degree of current seismicity, stresses are in some or most places nearly critical for failure by slippage on some pre-existing fractures within the upper 5 km. near the reservoir. There is some doubt about the magnitudes and direction of in-situ principle stresses. Most geological and seismological evidence points to high horizontal compression throughout eastern North America (Sbar and Sykes, 1973). Faults near Augusta (Prowell, et. al. 1975), 48 miles from the R. B. Russell damsite, have been shown to be thrusts dipping ESE. The one well-measured Charleston aftershock (Tarr, 1976), suggests northeasterly thrusting. Aftershocks of the August 2, 1974, quake near Clark Hill Reservoir inconsistently indicate either wrench or normal faulting, as do the Jocassee shocks (Talwani, 1976). The nearest in-situ hydrofrac test results (Haimson, 1976) suggest northeasterly thrust-fault orientations, as do some other tests in the past (Hooker and Johnson, 1969). Until further data suggest otherwise, a stress field of unspecified direction of high horizontal compression will be assumed, with faults appropriately disposed to accommodate thrust failure whenever adverse changes take place.

Though pore-pressure measurements in km.-deep holes in crystalline rock beneath reservoirs have never been made for proving the extent of reservoir-induced changes, circumstantial evidence points to considerable depths of hydraulic continuity. Mine waters indicate as much as 3 km. in some cases, the same order of depth as may be deduced from hot springs that discharge circulated meteoric

water. Spring discharge and piezometric measurements at several km. lateral distance from some reservoirs (Snow, 1972, 1973, 1974, Roksandić, 1970), likewise suggest propogation well beyond the reservoir slopes. No such data are at hand for Piedmont sites, but similar behavior is expectable.

An increase of pore-pressure in the rocks, when a reservoir fills, decreases effective stresses in the surroundings. These decreases more than offset the increases of effective stresses resulting from the deadweight of the reservoir. Whereas elastic subsidence is correctly computed from total-stress changes (à la Gough and Gough, 1970), failure depends upon effective stresses (Nur and Byerlee, 1971). Decrease of effective stresses is essential to induced failure (Snow, 1972), but the details of the mechanism are not obvious in any given topographic and tectonic setting. Though the filling of any reservoir might suggest that it should produce failure, it often does not, probably because sufficient stress changes are not developed. The history of deducible stress changes before filling may indicate whether or not the proposed reservoir should be expected to enhance seismicity or not. To outline the effective stress history, an adequate understanding of the geomorphic and hydrologic evolution of the region is required.

Then uplift and subsidence, heating and cooling, erosion and deposition, raising or lowering of water tables can be put into quantitative terms for comparison with reservoir loading. The reservoir change is superimposed, as the last event. The starting point of

the stress history is the time of the latest known faulting or seismicity, when it is logically assumed that stress was critical for failure somewhere within the field of reservoir effects. The history can then show whether or not continued criticallity has remained, or whether a stress threshhold exists to offer safety.

HYDROGEOLOGY OF PIEDMONT ROCKS

When changes in near-surface hydraulic potential occur, changes at depth follow. By what degree and to what depth the changes take place are matters of deduction from observed properties of the aquifers.

Faults, joints and foliation surfaces are conduits that make the metamorphic units aquifers relative to sheared or healed zones that are aquicludes. Throughout the reservoir region and elsewhere in the Piedmont, the lithologic units, most sheared and cataclastic zones and rehealed fault contacts stand vertically to steeply inclined, striking northeasterly. The writer believes the boundaries constrain the flow, so that the region is strongly anisotropic, with maximum permeability along the plane of contacts and the minimum, normal to it (Snow, 1969). The alternative favored by Sever (1964) is that flow is concentrated in planar openings parallel to the bedding, foliation and axial-plane cleavage. This may also be true, since the modest (25 gal. per day per ft) transmissibilities calculated from packer injection tests in drill holes (Stewart, 1962) are demonstrably due to fractures, not the rock mass. Joints not parallel to foliation also abound, but these are apparently not as effective or as continuous as conduits compared to those parallel to foliation. Thus boundaries limiting the extent of joints across foliation may control anisotropy. This would account for the ellipticity of a drawdown cone at the Georgia Nuclear Laboratory, and enhanced base-flow of streams flowing across the regional strike (Sever, 1964).

The depth of permeability is conjectural, since drill holes exceeding 400 or more ft in the Piedmont are rare, and mines are scarce. However, water occurs in fractures to all depths explored, even if the frequency and conductivity of open fractures diminishes with depth (Snow, 1968a). Water in deep mines, such as at 3.3 km. in the E. Rand mines, South Africa, though rare, shows that crystalline rocks have conduits capable of transmitting pore pressure, even if they are incapable of transmitting significant quantities.

LeGrand's (1967) interpretation of near-surface Piedmont hydrology in relation to topographic position is germain to this report. The water table generally lies within the saprolite, which may be from 0 to 150 ft. thick, but water reaches fractures below by filtering through that cover. The water table is 30 to 70 feet deep beneath hills, but coincides with streams in valleys. This shape indicates lateral drainage from upland recharge to lowland discharge areas. The depth of such circulation is a moot issue for water supply considerations: only shallow aquifers giving relatively high well yields are of interest. But for rock mechanics purposes, the full penetration of the influence of different surface potentials is the significant property. The depth of concern is probably as deep as the zone of shallow earthquakes. Observed earthquakes clearly induced by reservoirs (e.g., 2-3 km. at Koyna, India) suggest deep penetration.

The water table shape bears a complex relationship to the rate of recharge through saprolite underlying slope areas, the distribution of permeability with depth and position, and the slope

angle. The distribution of potential at depth depends on the shape of the water table and the orientation and permeability variations along conduits, such as faults and joints. At great depths, the permeable features of interest are faults, whereas nearer the surface, the features of importance are largely joints that open with unloading or erosional releases of overburden and tectonic loads. The depth of weathering is paramount near the water table. Saprolite is lacking at the level of important streams like the Savannah River, which expose bedrock. There, joints and faults abound. Below a few hundred feet, presumably only faults are important. Doubtless faults are anisotropic and heterogeneous conduits, but for lack of information on specific ones, it is assumed that they function as near-vertical planar conduits, within which a predictable circulation takes place according to any assigned or supposed pattern of changing permeability. If the pattern is only depth-dependent, the circulation from high-potential recharge regions under topographic divides to low-potential discharge regions under streams is symmetrical. Complex cellular flow patterns, shown by Tóth (1962) and by Freeze and Witherspoon (1967), depend upon the geology and configuration of the water table, which mimics the topography. The potential at the greatest depths, our present concern, depends upon the major topographic features, which give scale to the size of the major circulation cells. Figure 2 illustrates the ideal pattern predictable for isotropic homogeneous ground or for a vertical conduit in the same plane. In the Piedmont, major divides between SE-flowing rivers lie roughly 20 to 25 km.

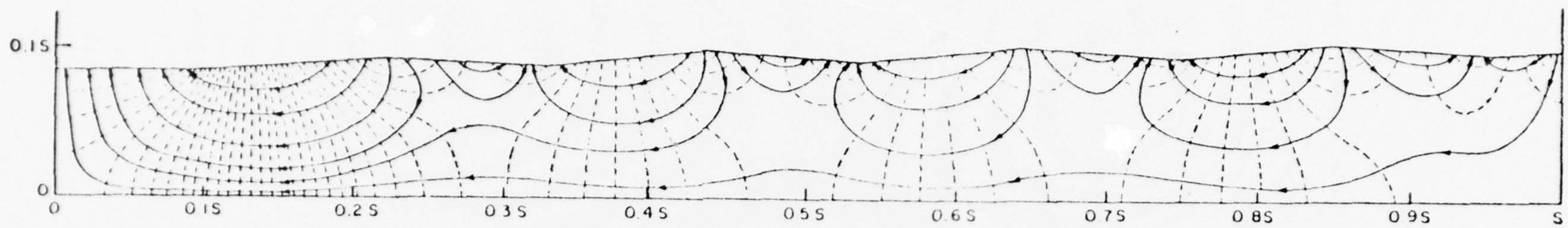

Figure 2.

Regional Hydraulic Potential Distribution In Homogenous Material From Major Divide To Stream.

apart, and a cell of half that width can extend to at least such depths if hydraulic continuity exists. At shallow depths, nested cells relate to the finer and finer drainage systems of the dendritic stream pattern. But potentials, and consequently pore pressures at hypocentral depths, are most dependent upon the deepest, or regional circulation cells. Changes in potential at depth thus reflect such boundary potential changes as occur by reservoir filling, valley alluviation with corresponding water table rise, valley incision, etc. If there are deep-penetrating but isolated, dead-ended conduits like faults, potential changes in such static water columns will respond to the potential change in the deepest overlying circulation cell, and therefore also respond to boundary potential changes.

The time for a change to take place (Howells, 1972) after a boundary potential is changed depends upon the depth in question and upon the diffusivity. The latter is the ratio of permeability to storativity, both of which decrease with depth (Snow, 1968). The rate of propagation of a transient may not decrease with depth; indeed, there is seismic evidence at Koyna that once the pore pressures induced by the reservoir had penetrated the Deccan traps into the granitic basement, seismicity spread rapidly in lateral directions. Talwani (personal communication, 1976) has some of the first measures of the obscure diffusive properties of basement rocks, found by measuring the three-dimensional spread of induced earthquakes in the Lake Jocassee region. It is conceivable that pressures may diffuse so quickly that in some cases, induced earthquakes may occur over

only a few months' span (as at Monteynard, France), whereas in other cases (Lake Mead, Clark Hill Reservoir), the transient may take many years to complete the hydrogeological-seismic stress adjustment. Experience at many reservoirs suggests that the span of usual induced seismicity is a few years. The Jocassee data are consistent with that view. Similarly, a new reservoir like the Richard B. Russell Lake should develop a seismic response in 2-3 years.

When a major conduit, such as a fault, lies parallel to a reservoir, an extensive boundary length becomes an equipotential (the head is the reservoir elevation) with a sharp drop of potential at the dam, producing under-seepage. At depth immediately below the dam, the increase of potential is equal to half the reservoir depth; at shallow depth below the reservoir, the increase approaches the full submergence, diminishing upstream and with depth below the thalweg. If regional groundwater circulation is dominated by faults parallel to the river rather than faults tributary to and across the rivers, decreases of effective stress effect greater fault areas and generally have greater magnitude.

It is concluded that pore-pressure changes at deep levels in the vicinity of Richard B. Russell Reservoir, which crosses most faults, may be approximated by one-half the change at the discharge boundary. A 200 ft lake would increase pore-pressure in a deep fault region about 43 psi., though clearly the changes range from 0 to 86 psi.

Stress changes from hydraulic events, past and future,

are important aspects of the effective-stress ciicumstances attending a reservoir. Another aspect is the tectonic setting.

TECTONIC EVOLUTION

The Appalachian Mountains are believed to have formed during late Paleozoic time by the subductive suturing of a North American plate to a proto-Atlantic plate (Hatcher, 1972). In the compressive orogeny, great shortening and thickening of the crust was accomplished by folding and imbricate overthrust faulting. The roots of the nappes are now exposed, because there has since been a great deal of erosion of the mountain-mass. The rocks are late Pre-Cambrian to mid-Paleozoic in age, composed of regionally-metamorphosed volcanics, graywackes, shales and plutonics, with quite different grades of metamorphism from one SE-dipping thrust sheet to another. Numerous cataclastic zones form lithologic boundaries.

During the Triassic, the Atlantic Ocean opened. Near the continental margin, there developed extensional faults bounding graben and half-graben troughs in which were deposited coarse arkosic sediments and volcanics of the Newark Series. The trough system extends from the Maritime Provinces southward intermittently to Georgia. The Dunbarton Trough underlies coastal plain sediments at the Savannah River Plant in South Carolina and across the River in Georgia (Siple, 1967). The NE-trending normal faults indicate that while the continental edge was in a zone of divergent mantle flow, the least compressive stress, σ_3, was NW-SE and the major stress, σ_1, was vertical.

Vertical diabase dikes with consistent NW strike cross-cut the Triassic faults. They are Jurassic in age. They indicate fluid injection into rock whose stress field was σ_1 horizontal, parallel

to their NW strike, and σ_3 horizontal, northeasterly. May (1971) showed that upon reconstruction of the early Mesozoic geography, the Jurassic dikes in the circum-Atlantic continental margins of North and South America, Europe and North Africa had a radial pattern suggestive of expansion from a central area now occupied by the Blake Plateau. Change of position of the margins relative to such a zone of mantle divergence in the Atlantic could reasonably account for a Triassic to Jurassic increase of northwesterly compression, while other stresses remained relatively unchanged.

At many Piedmont and Blue Ridge localities (Birkhead, 1973) there are found silicious breccia-filled fractures, otherwise called flinty-crushed rock zones (Conley and Drummond, 1965). These cut the Jurassic dikes at small angles, since they are generally oriented west or northwesterly and have steep dips. As healed fractures, they may record a different tectonic stress system, either extensional fracturing or faulting. Hatcher says that careful geologic mapping shows no displacements along those healed features, but D. T. Secor has mapped a flinty crush-rock zone that truncates rock units (Talwani, 1976). Open joints, then, record a time when σ_1, and σ_3 were more nearly E-W and N-S, respectively, than during Jurassic dike formation.

It is not known exactly when compressive tectonic mobility returned to southeastern North America, for the evidence of Cretaceous faulting would be buried under the coastal plain, where there may be Early Cretaceous, possibly even Jurassic sediments. The Triassic faults bounding the Dunbarton Basin and buried by late Cre-

taceous sediments have not been displaced (Marine, 1976). Reverse faults of NE strike cutting late Cretaceous through Quaternary-age beds do not record the inception of NW compression, but do record a long period of activity that could extend to the present (Prowell, 1975, 1976). Zupan and Abbott (1975) give evidence of post-Eocene thrusting. In the Charleston area, a synclinal flexure of late Cretaceous basalt and overlying Santee Limestone strikes northward (Ackermann, 1976). The Beaufort high (Higgins, et. al., 1976) parallels the South Carolina coast. It is probably faulted on its NW flank, and involves Oligocene and older strata. Siple (1967) describes oriented clastic dikes on the Savannah River Plant cutting the Hawthorne Formation of alleged Miocene age. It is not certain at this time that those dikes are of seismo-tectonic origin, and the Hawthorne is conceivably a saprolitization product of the underlying late-Eocene Barnwell formation (Marine, personal communication, 1976). Evidently the dikes described by Zupan and Abbot imply post-Eocene earthquakes. Much work remains to be done to define Tertiary and Quaternary tectonics of the eastern seaboard.

Movement of the continental plate away from the mid-Atlantic spreading rift may have placed the continental margin over a region of horizontal mantle flow. Thus the plate would transmit high horizontal stresses imparted by base shear. The minimum stress, σ_3, became vertical and thrust faults developed when the deviator stress became critical. Furthermore, a decrease of vertical stress in excess of decreases of horizontal stresses is a likely consequence of Appalachian

erosion, cooling and isostatic uplift. Such a history is recorded by strong tilting of the Cretaceous erosion surface beneath the coastal plain sedimentary wedge. Piedmont uplift is implied by subsidence recorded east of the Fall Line; decreasing dips of succeeding younger horizons indicate tilting. Loading, subsidence and heating may have inhibited faulting beneath the wedge, while faulting could have been activated in the Piedmont, where the evidence has been stripped off. Only at the wedge-edge, near the Fall Line, is fault evidence preserved.

Data indicating the state of stress and tectonic style of southeastern United States is inconsistent in many instances, but the preponderance of evidence points to continued horizontal compression as the mechanism of earthquakes, pop-ups, quarry movements and possible faulting in eastern North America (Sbar and Sykes, 1973). The direction of maximum horizontal compression is uncertain for SE United States. If the NE-SW major compression demonstrated as the modern stress model for most of eastern North America pertains also to southeastern United States, it would indicate that there has been a local reversal of the directions of σ_1, and σ_2 since the early Tertiary thrusting. The southeastern data do not support the hypothesis that stress parallels the Appalachian trend. The directions of σ_1 axes box the compass at Atlanta, Georgia (Sbar and Sykes, 1973), but in North Carolina (Hooker and Johnson, 1969) and at Rapidan, Virginia, σ_1 has been found to be northeasterly. Haimson (1976) measured in-situ stresses by hydrofracing at the Bad Creek pumped-

storage site near Lake Jocassee, S.C., determining that σ_1 is northeasterly, and σ_3 is vertical. The November 22, 1974, quake near the Charleston, S.C., site is interpreted as a thrust-fault event with compression in the NE quadrant (Tarr, 1976). However, focal-plane mechanisms reported from aftershocks of the August 2, 1974, shock near Clark Hill Reservoir at McCormick, S.C. (Talwani, 1976) were of both normal and wrench-fault configuration, with σ_3 WNW and $\sigma_1 = \sigma_2$ equal to the overburden, the only model consistent with the data. Jocassee quakes support the thrust model near the surface, but deeper shocks suggest a normal-fault model (Talwani, personal communication, 1976). Reported shocks on major faults such as the Brevard, Goat Rock and Towaliga zones are more consistent with a NW-SE compression than with a NE-SW direction; no prevalent system of NW striking thrusts has been reported.

In consideration of conflicting stress data, it is premature to rule out the possibility of various stress models, and it is clear that further data will be needed to determine adequately the regional stresses even in qualitative form. The preponderance of information does favor the hypothesis that high horizontal stresses exist generally (not exclusively) in the southern Piedmont region. For interpretation of geomorphic and reservoir-induced stress changes, a thrust pattern is most likely, but the normal-fault alternative will be analyzed also.

GEOMORPHIC EVOLUTION

Because there are subtle differences, making one reservoir site seismic and another non-seismic, the small stress changes superimposed on regional tectonic stresses by surficial events need to be enumerated. The history of changes can be deduced from the geomorphic record, upon which the proposed reservoir effects will be superimposed.

Though much has been written about Southern Appalachian geomorphology, it remains imperfectly understood. For instance, why does the drainage divide now lie east of the Blue Ridge, much closer to the Atlantic than to the Gulf of Mexico? The divide is on an old 1500-2500 ft-high erosion surface dissected by SW-flowing streams.

This is the Dahlonega Plateau of La Forge (1925) or the Asheville surface of Haselton (1974). The east-flowing streams rise on a steep, dissected scarp, over 1000 ft high, called the Blue Ridge Front, and because their gradients are great, these streams are progressively capturing the headwaters of the sluggish, SW-flowing streams on the Plateau (Acker and Hatcher, 1970). Because the Front sinuously cross-cuts NE-trending formations contrasting in lithology and erodability, the Front is believed by the writer to be largely an erosional feature, though it is not fully understood how it evolved.

The fault-origin hypothesis of White (1950) is supported by such evidence as (1) linearity, (2) abruptness of the declivity, (3) steep stream gradients, falls and hanging valleys, (4) truncated ridges and (5) truncated spurs, (6) fault breccia, (7) slickensides,

(8) alignment of streams parallel to the scarp, and offset of fault breccia across the scarp (Haselton, 1974). They would interpret the Dahlonega as an upthrown, more dissected part of the Piedmont peniplain. If it is a fault, it seems likely to be an ancient one, though the deep stresses deduced from first motions of Jocassee quakes at the Blue Ridge Front (Talwani, personal communication, 1976) are consistent with a modern normal-fault mechanism. The principle objection to the fault hypothesis is that parallelinity to structure is restricted to the reentrant in South Carolina; elsewhere the Blue Ridge Front cross-cuts the metamorphic units and particularly the Brevard cataclastic zone, oft-suspected of being a major recurrent fault.

East of the Blue Ridge Front is a subdued, mildly dissected terrain known as the Piedmont, a plain into which streams have eroded to develop relief which varies from 500-odd ft near the Front, to about 250 ft near the Fall Line. The latter is the SE boundary of the Piedmont, so-called because it is the limit of navigation, where the master streams leave the metamorphics to flow on soft sedimentary and alluvial materials of the Coastal Plains. Whereas many more streams of the Piedmont flow nearly on strike with the steeply-foliated, NE-trending metamorphics, they are parts of a dendritic pattern developed upon a homogeneous alluvial cover, now removed. The trunk streams are SE-flowing, consequent to a tilting Appalachia. In the headward extremes of the Piedmont, as on the Dahlonega Plateau, more perfect adaptation to foliation and jointing is shown by subsequent drainage patterns.

In one important aspect, the Appalachian topography resembles Africa, with which it has a common continental ancestry: two or more major ancient erosion surfaces are evident. Where relationships are more clear in Africa, the oldest surface is evidently Jurassic in age, dating from the breakup of Gondwanaland, and the most extensive, the African surface, is Cretaceous. Erosional development has been faster in the southern Appalachians because of higher gradients, and greater run-off rates. Before late Cretaceous and Tertiary recutting, the Piedmont was nearly planar, as indicated by soundings through the Coastal Plain sediments. Thus the Dahlonega Plateau could be a much older surface and the Blue Ridge summits even more so. The few monadnocks (like Graves Hill, Figure 5) protruding above the well-bevelled Piedmont surface support the view that the Dahlonega Plateau once extended eastward.

As indicated in the stress history to follow, erosion and uplift have dominated the Appalachian chronicle, while burial and subsidence have characterized the coastal plain. Both regions have moved to maintain pseudo-isostatic balance, tilting progressively eastward, apparently as a unit. If there have been major fault dislocations of once-continuous erosional surfaces, they are either hidden beneath the coastal deposits or obscured by saprolite developed on Piedmont rocks lacking marker horizons. Slickensided seams of clay or manganese and iron oxides and hydroxides found in the Piedmont are believed (Deininger, 1976) to be of pedogenic origin, not faulting. Only at the Fall Line, where stratigraphic cover is thin,

are unquestionable faults likely to be found.

A marked difference of magnetic character and grain noted by Zeitz, et. al., (1976) suggests a different origin of the basement beneath the Coastal Plain from that of the Piedmont. Phillip (1976) interprets the gravity anomalies near Charleston to indicate E-trending faults having displacements up to 1000 ft. Higgins et. al. (1976) feel that the Orangeburg scarp lying about 25 miles SE of the Fall Line is a fault scarp, separating regions of different sedimentary facies. Thus the Fall Line could be within a zone of regional faulting, making tilt projections (Figure 5) onto the Piedmont quite questionable measures of uplift.

During the last 150 million years, the rate of landform development has been controlled by saprolitization rates, fostered by high temperatures and rainfall. Deep saprolite existed before the late Cretaceous Tuscaloosa Formation buried and reworked it. Intact foliation in kaolin residuum is found under the unconformity. The coarse sandy to pebbly Tuscaloosa beds record a long period of high-energy stream erosion, cutting through an old saprolite cover into unweathered crystalline bedrock, much of which is granitic. Drilling has shown (Siple, 1967) that there was as much as 150 ft of relief at the position of the Savannah River Plant, and presumably there was more relief inland. Subsequent coastal formations are all fine-grained, more calcareous, shallow marine deposits of saprolite-derived detritus generally lacking coarse clastics (Siple, 1967, and Owens, 1970). Even the Pleistocene beds are fine-grained sand and muds,

while the Savannah system has incised valleys into bedrock on the Piedmont. Climatic control of tectonism, or vice-versa, is evident from the change to fine-grained clastic and carbonate sedimentation after late Eocene time.

Douglas (1974) has summarized research on Piedmont saprolite age, concluding that it is pre-Pleistocene, a million years old at a minimum. In the case of the faults cutting reactor containment-vessel excavations at North Anna, Virginia, or the fault cutting the diversion channel at Richard B. Russell Dam, undisturbed horizontal red-yellow podsol marker beds indicate no fault displacement during the last million years. A similar conclusion of saprolite age can be drawn from the writer's observations of soil formation in coastal terrace deposits. The lowest terraces (the present tidal flats, the Pamlico at 25 ft and the Talbot at 42 ft elevation) are unweathered, but the higher ones are saprolitized. Just south of Springfield, Ga., the Penholoway surface (70 ft) is characterized by a 2-ft leached yellow horizon underlain by about 10 ft of mottled, crenulated soil enriched with red iron oxides. Though interglacial correlations are uncertain at this time, the normal sequence would suggest an age of about 600,000 years for the Penholoway soils, thus rapid saprolitization is evident, a process that has gone on at least since Cretaceous time.

While climate controls weathering, it also controls erosional removal, in conjunction with relief. But relief is controlled also by isostatic uplift, which in turn responds to erosion. A mountain

chain of low-density crustal rock buoyed up by high-density mantle rock has altitude controlled by the thickness of the crust and the density contrast. Like an iceberg whose tip is melting, it continues to rise above sea level. The altitude diminishes much more slowly than the ground is eroded. It will be shown below that since the mid-Cretaceous, there has been about 2,270 ft of uplift of the Piedmont in the present vicinity of the R. B. Russell Reservoir, but topography stands only about 425 ft lower now than formerly. The evidence of uplift is plotted on Figure 5, revealing the pre-late-Cretaceous unconformity beneath the Savannah River Plant, dipping 36-40 ft/mile southeasterly. Near Charleston, S.C., it is 4,000 ft deep and dips about 42 ft/mile (Stephenson, 1914 and Ackermann, 1976). Succeeding unconformities dip at flatter angles, recording the tilt since each unconformity was preserved. On Figure 5, these have been projected back over the Piedmont along profiles appropriately bent as in a continuous beam.

The relationships between erosion and uplift, alluviation and subsidence were computed using simple models and Archimedes Principle. Its derivation is included here because the concept has not previously been applied to induced seismicity.

Illustrations A & B follow:

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GEOLOGICAL AND SEISMOLOGICAL EVALUATION OF EARTHQUAKE HAZARDS A--ETC(U)
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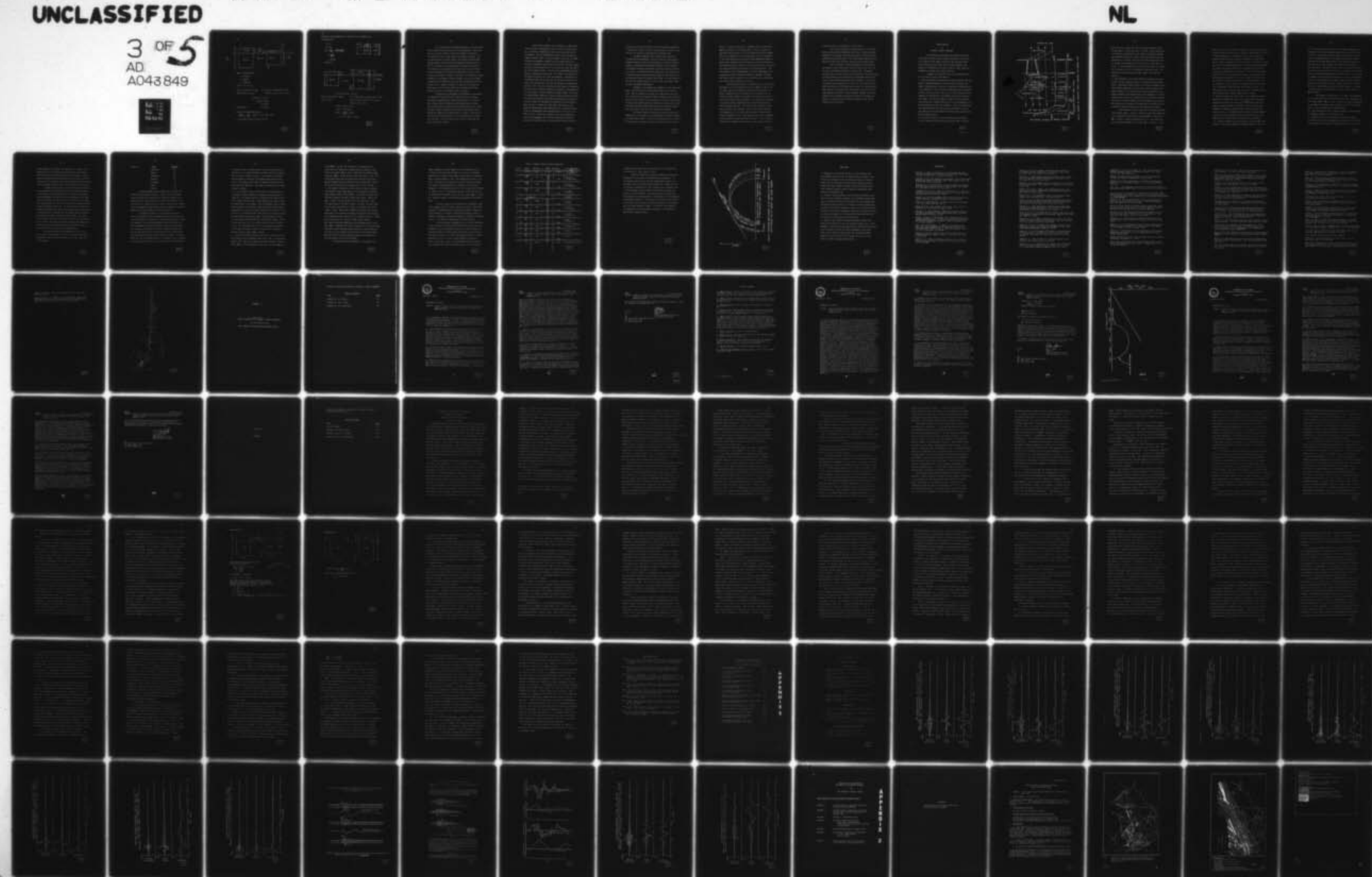
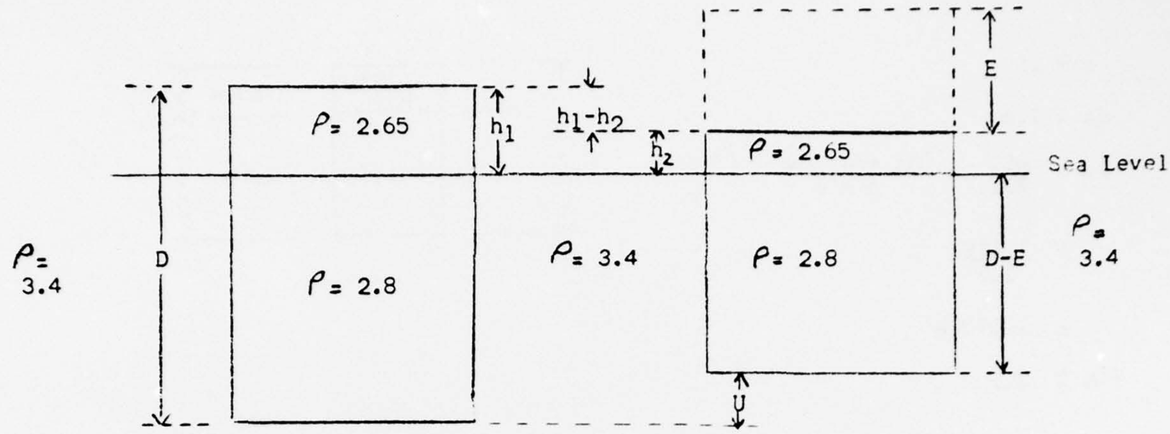


(A)



When D = crustal depth

E = erosion

U = uplift

h = altitude,

then $E - U = (h_1 - h_2)$

$2.65\ h_1 = (D-h_1)(3.4 - 2.8)$ and $2.65\ h_2 = (D-E-h_2)(3.4 - 2.8)$

$(2.65 + 0.6)\ h_1 = 0.6\ D$ $\quad$ $(2.65 + 0.6)\ h_2 + 0.6\ E = 0.6\ D$

$$3.25\ (h_1 - h_2) = 0.6\ E$$

$$(h_1 - h_2) = .185\ E$$

$$U = .815\ E$$

Thus erosion, $E = 1.23\ U$

If $U > 0$ is a known uplift in ft,

$$\Delta\sigma_x = -\frac{E}{1-\nu}\ \frac{U}{a} \approx -.34\ U \text{ psi, since}$$

a, the earth's radius, is 2.09×10^7 ft.

(B)

Similarly, when aggradation of a terrain occurs, subsidence may be computed by:

$e \simeq .5$

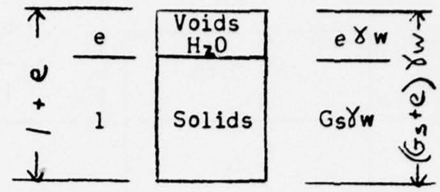
$G_s = 2.6$

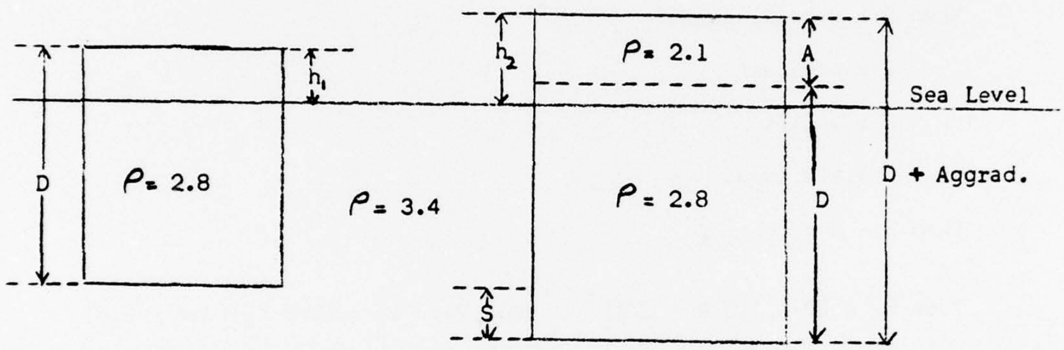
$\gamma_m = \dfrac{\text{wt.}}{\text{vol.}} = \dfrac{(G_s + e)\gamma_w}{1 + e}$

$= \dfrac{3.1\gamma_w}{1.5}$

$= 2.07\gamma_w$

$\rho_m \cong 2.1$





$$S = h_1 - h_2 + A = A - (h_2 - h_1)$$

$2.8\,h_1 = (D - h_1)(3.4 - 2.8)$

$3.4\,h_1 = 0.6\,D$

$2.1\,A + 2.8\,(h_2 - A) = (D - h_2 + A)(3.4 - 2.8)$

$3.4\,h_2 + 2.1\,A - 2.8\,A - 0.6\,A = 0.6\,D$

$3.4\,h_2 - 1.3\,A = .6\,D$

$$3.4\,h_1 = 3.4\,h_2 - 1.3\,A$$

$$1.3\,A = 3.4\,(h_2 - h_1)$$

$$(h_2 - h_1) = \frac{1.3}{3.4}A = .38\,A$$

$$S = A - (h_2 - h_1) = .62\,A$$

It is believed that the Piedmont attained a very nearly plane aspect during Pliocene time except for a new monadnocks. Plane horizons are currently visible in excavations through the saprolite. The stream-cut valley slopes truncate the saprolite horizons. During some interval of changed climate, that surface was covered with sediment derived from the Blue Ridge, possibly attaining as much as 200 ft of thickness and extending almost to the Blue Ridge Front. The continuous cover probably did not extend into an area of strike ridges and subsequent and trellised stream patterns having angular junctions and evidence of piracy in the Salem, S.C. Piedmont re-entrant. Elsewhere on the Piedmont, streams consequent to the fill developed a dendritic pattern which has persisted after superposition onto the foliated rocks. Superior adjustment of drainage to lithology and fracturing in the re-entrant suggest more prolonged exposure compared to the rest of the Piedmont, which is exhumed.

The present hilly topography of the Piedmont is the product of intermittent incision into the resurrected Pliocene peneplain, with channel sedimentation at times refilling parts of the valleys. Master streams like the Savannah and many tributaries now flow on fresh bedrock without alluvial fills, reflecting steeper than natural gradients, probably resulting from continued southeastward tilting. Whereas the gradient of the Savannah River is about 1 ft per mile in the alluvial reach below the Fall Line, its gradient above is about $3\frac{1}{4}$ ft per mile. It is very rare to find a river of such size that lacks alluvial bed material.

Coastal Plain sediments of late Cretaceous to Miocene age record a history of epeirogenesis that is the key to understanding the late Tertiary and Quaternary events less well recorded in the stratigraphy. For full descriptions of these units, the reader is referred to Siple (1967). As seen in Figure 5, each unit is a wedge thickening southeasterly, separated from succeeding units by an erosional unconformity that beveled the top of the next older landward wedge-edge so that young units lie on successively older, even Paleozoic rocks towards the west. The dip of the unconformities decreases upwards, consistent with their ages. The existence of erosional unconformities indicates that uplift was spasmodic. Interruptions of sedimentation show that the Fall Line has not been a hinge line, for coastal-plain regions were also uplifted, stripped, and subsequently reburied. After the coarse Tuscaloosa clastic sequence was deposited, late Cretaceous to Miocene sediments were dominantly fine-grained and of shallow marine, littoral, lagoonal, and tidal origin. The isostatic balance between sedimentary loading and basin subsidence has been very sensitive throughout the Tertiary and Quaternary, during which as much as 4,000 ft of deposition and subsidence has taken place at about sea level. Because flat slopes make large changes of the shore-line position when uplift takes place, it is apparent from the extent of unconformities that individual uplift events were on the order of 50 ft. These could conceivably have been accompanied by one or more earthquakes, like the Prince William Sound quake and regional tilt of March, 1964. The events could also have been dis-

continuous but quiet epeirogenesis of the sort currently proceeding in northeastern Georgia. Uplift is occuring there at a rate of 7 mm. per year, and tilting, 3.5 mm./year/100 km. (Meade, 1971).

The modern Piedmont erosion surface, mostly carved on steeply-foliated metamorphics, continues essentially uninterrupted eastward of the Fall Line onto soft Cretaceous and Eocene sediments. Locally, the downcutting of subsequent Piedmont stream tributaries has exhumed the basement unconformity and formed west-facing sedimentary cuestas. The dissected surface underlain by soft sediments near the Savannah River is called the Aiken Plateau in South Carolina and the Louisville Plateau in Georgia (Cooke, 1936). It slopes about 8 ft per mile from elevation about 600 ft at the Fall Line (Siple, 1967). Its age is presumably Mio-Pliocene.

Southeast of the plateaux is a sequence of seven Pleistocene marine terraces covering a strip 80-90 miles wide to the Atlantic shore. Each is apparently the result of a still-stand of sea level and a beveling of older deposits to form a SE-facing scarp, often surmounted by sand deposits that are remnants of a barrier island system. Generally flat, swampy ground lies shoreward of each bar, but succeeding higher terraces are better and better drained, possibly because their low initial slopes have been tectonically steepened.

The highest terrace, bounded by an irregular shoreline of submergence to the northwest, is the Brandywine or Hazlehurst Terrace, at elevation about 220 ft. Below it is the Coharie Terrace at 215 ft. The scarp below the Coharie is steep and nearly linear across South

Carolina. Called the Citronelle or Orangeburg Scarp, it bends westward to lie tangent to the Savannah River. There the Coharie and Hazlehurst Terraces pinch out, so the scarp bounds the Aiken Plateau. Thus, it is erosional, not a fault line scarp, for its conformation to the river indicates that an estuary formed, then the scarp formed by lateral river migration upon the estuary fill. Below the Coharie is the Sunderland Terrace, elevation 170 ft, bounded below by the sinuous Surry Scarp, which also bends tangent to the Savannah River. From the evidence of river drowning between sea-level withdrawals, it is presumed that alluvial conditions changed far upstream, resulting each time in gravel alluviation and a water table rise, alternating with times of gravel erosion and river fall.

Below the Surry Scarp is the Wicomico Terrace at 100 ft, the Penholoway at 70 ft, the Talbot at 42 ft, the Pamlico at 25 ft, and the modern salt flats lying behind the barrier sand islands. The present drowned mouth of the Savannah River, the Broad River, St. Helena, Charleston Harbor, etc. are due to an eustatic rise of sea level during glacial retreat elsewhere. The correlation of the seven terraces with glacial interstages has not been made because only five interstages are known. Yet, tiers of seven terraces or pediments have been noted elsewhere, such as along the Rocky Mountain Front (Markette, et. al., 1976), which suggests continental-scale climatic variations. Flint (1940, quoted by Siple, 1967) considered the Surry Scarp the highest Pleistocene feature. It is only speculation then to assume the seven terraces to have formed during the

1.5 million years or so ascribed to the Pleistocene.

Cooke (1936) envisioned each marine terrace to have formed during a high sea-level interglacial still-stand. Continuous uplift resulted in a succession of terraces because of the uplift occurring during low-level glacial stages. This interpretation implies tectonic quiescence rather than cataclysmic seismic events attending uplift.

There is evidence of former Savannah River alluviation on the Piedmont. Siple (1967) notes Pliocene alluvial gravel up to 20 ft thick on interstream divides near the Fall Line. Topographic benches along the shores of Clark Hill Reservoir and the future Richard B. Russell Reservoir have been detected on topographic maps (See Figure 5), some of which preserve thin gravel deposits. On the South Saluda River are bouldery gravels at 50 ft and 100 ft above the present river (Haselton, 1974) which flows on rock. The modern Savannah River Channel near Savannah River Plant flows on 5 to 30 ft of alluvium, possibly the result of coastal drowning. Whereas the alluvial terraces on the Piedmont are genetically related to the marine terraces on the Coastal Plain, the work of correlating these sets of surfaces has not been done.

LOADING HISTORY

AT

RICHARD B. RUSSELL RESERVOIR

It is instructive to evaluate the changes of stress up to the time of latest certain faulting (post-Eocene), then to see if a consistent trend towards instability has persisted between latest faulting and the present time of modest seismicity, and finally, to superimpose on the prior events the stress changes attributable to filling of the future reservoir.

A summary of stress effects due to the following events are to be found in Table I and Figure 3:

1. The late Cretaceous Tuscaloosa and Ellenton Formations were laid down on a subsiding basement as the Blue Ridge and Piedmont were eroded. Saprolitization continued, as suggested by detrital kaolin in the Tuscaloosa. Since Tuscaloosa deposits are coarse continental clastics, even to the coast (Gohn, et. al., 1976) there were no inundations nor alluviations on the Piedmont as must have occured at later times. The Ellenton Formation records a time of decreased relief inland and a transgressive sea, since its predominantly fine-grained sediments are tidal and estuarine. Thus, it is likely that the rugged mid-Cretaceous erosion surface was reduced to a peniplain with less water-table decline than would have occured had the terrain remained rugged.

2. As scaled on Figure 5, the late Cretaceous uplift totalled 1,000 ft, producing an effective stress change: $\Delta\sigma ex$ = -344 psi.

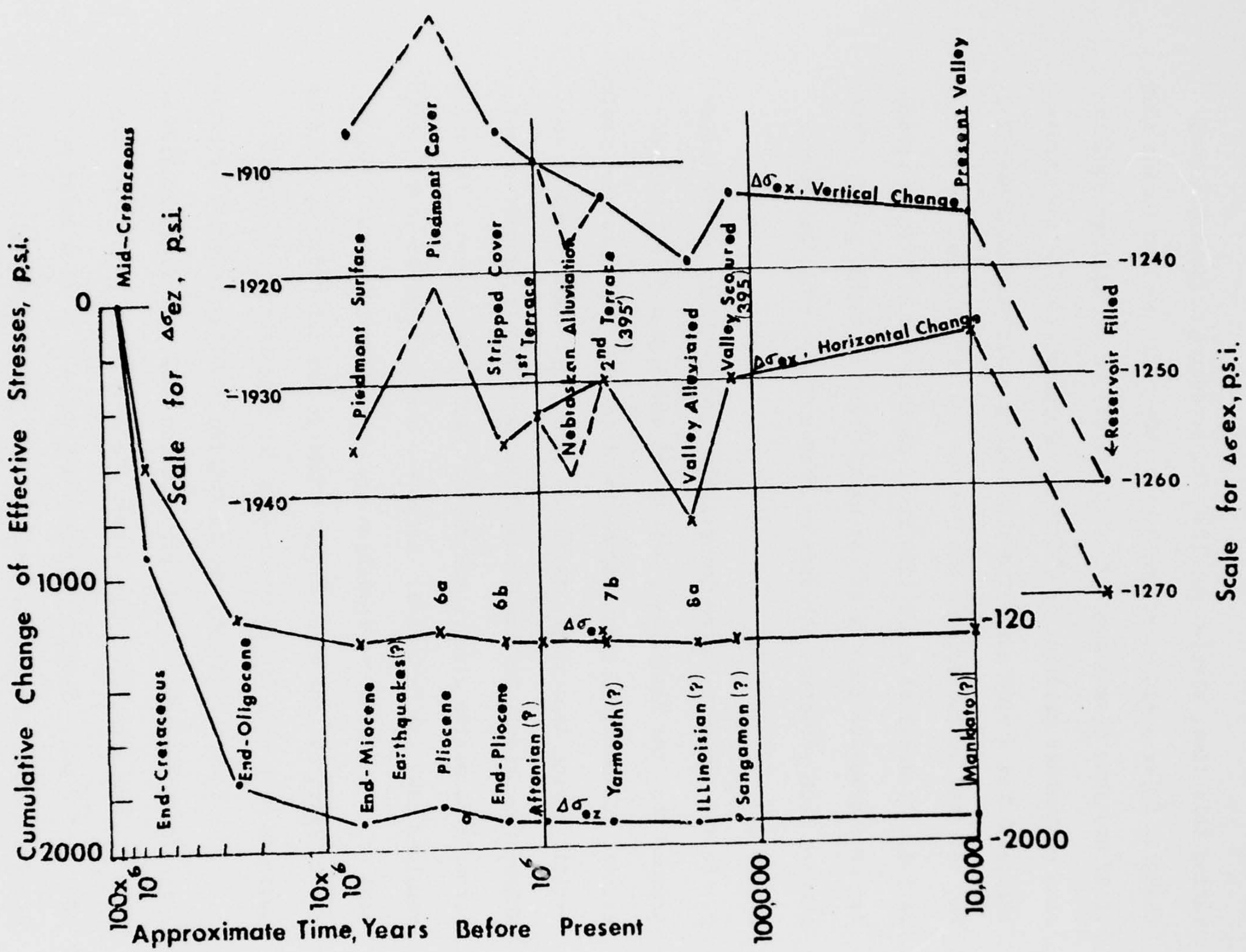


Figure 3. HISTORY OF EFFECTIVE STRESS CHANGES, R.B. RUSSELL SITE

During this time, erosion was 1230 ft, producing effective stress changes: $\Delta\sigma ez$ = -1422 psi and $\Delta\sigma ex$ = -609 psi. Cooling during 1230 ft of erosion, slow enough (75 x 10^6 years) to maintain an equilibrium geothermal gradient of 1°C/40 m, produced an effective stress change: $\Delta\sigma$ ex = -160 psi. The water table would have declined 1230 ft, the same as the erosion but for the loss of at least 100 ft of relief. It declined about 1230 ft at divides and 1130 ft at streams, for an average of 1180 ft at the bottom of circulation paths. That changed both effective stresses by $\Delta\sigma ez = \Delta\sigma ex$ = + 511 psi (See Figure 2).

3. Eocene deposits on the Coastal Plain were voluminous but finer-grained than the Tuscaloosa, because of diminished relief on Appalachia. Glauconitic sands and marls of the Congaree Formation record neritic marine deposition, as do the sands, clays and limes of the McBean Formation. The red sandy clays overlying limestones of the Barnwell Formation also record shallow marine deposition. The shore remained near the Fall Line. Oligocene cherty fossiliferous neritic beds of the Flint River Formation are found seaward of the Savannah River Plant, but the attitudes of contacts are ill-defined, so it is included here with the Eocene events for computation of uplift.

Eocene-Oligocene uplift totaled 950 ft, producing effective stress changes: $\Delta\sigma ex$ = -327 psi. During this same time, erosion was 1170 ft, producing effective stress changes: $\Delta\sigma ez$ = -1346 psi and $\Delta\sigma ex$ = -578 psi. Cooling corresponding to 1170 ft of erosion produced a further effective stress change: $\Delta\sigma ex$ = -152 psi. A water

table decline of the full amount of erosion, 1170 ft, with plane terrain maintained produced effective stress increases: $\Delta\sigma ez = \Delta\sigma ex = + 504$ psi.

4. Miocene deposition is recorded in the very extensive Hawthorn Formation, generally sandy, phosphatic sandstones of shallow marine origin. Pliocene inundation of the Coastal Plain is indicated by marine shell beds of the Waccamaw Formation. The angular relationship between the base of the Miocene Hawthorn and the supposed Pliocene erosion surface on the Piedmont at the vicinity of R. B. Russell Dam suggests uplift of 175 ft in the Mio-Pliocene interval. The resulting effective stress change was: $\Delta\sigma ex = -60$ psi. Erosion during this time was about 215 ft, producing effective stress changes: $\Delta\sigma ez = -247$ psi and $\Delta\sigma ex = -106$ psi. Cooling to correspond with the erosion produced a horizontal effective stress change: $\Delta\sigma ex = -28$ psi. The water table decline, of amount equal to the 215 ft erosion, produced equal effective stress changes: $\Delta\sigma ez = \Delta\sigma ex = +93$ psi.

5. Oriented clastic dikes (Siple, 1967, p. 59) cutting the Hawthorn Formation are probably the result of one or more major earthquakes which may have recurred any time during the late Tertiary unloading sequence, excepting periods of alluviation. Since sedimentary dike formation is fostered by uncemented fine granular materials that readily liquify, it is suggested that the dikes are penecontemporaneous with the overlying injected sequence of Hawthorn rocks, thus quakes may have preceded Pliocene alluviation on the Piedmont.

6a. It may be supposed that the fine-grained clastic landward equivalents of the Pliocene limestones (Waccamaw) covered a large part

of the Piedmont, and that it was upon this vanished formation that a consequent dendritic river drainage pattern developed before Pleistocene time. The extent of cover is estimated by the change from dendritic to subsequent pattern in the Walhalla-Salem, South Carolina, reentrant, at elevation about 1200 ft. Over a drainage distance of about 60 miles, a river flowing on alluvium would have fallen not more than 200 ft. The depth of cover in the R. B. Russell area could have been on the order of 200 ft, if much of the present 700 ft of fall from the Saluda River capture points (Haselton, 1974) to the region of the damsite has been developed by Pleistocene tilting. An aggradation of 200 ft of alluvium would have produced transient stress change of: $\Delta\sigma ez = +153$ psi and $\Delta\sigma ex = +66$ psi. Heating due to 200 ft of burial would have changed effective stress by: $\Delta\sigma ex = +26$ psi. The ground accordingly may have subsided 124 ft to change effective stress by: $\Delta\sigma ex = +43$ psi.

The increase of elevation was 76 ft, 38% of the aggradation, but the water table rose 200 ft relative to the rocks, decreasing effective stress: $\Delta\sigma ez = \Delta\sigma ex = -87$ psi. Evidence of Pliocene aggradation is the presence of alluvial gravel deposits up to 20 ft thick (Siple, 1967, p. 62) on interfluves on the Aiken Plateau.

6b. These loading effects of a temporary Pliocene fill were removed by subsequent stripping of the Piedmont veneer.

7. Pleistocene events are best recorded in the Coastal Plains. Fluctuations of sea level, progressively retreating as the continent rose, producing seven terraces of descending altitude. At the R. B.

Russell Damsite, as elsewhere in the Piedmont, the incision of the Savannah River and its tributaries was interrupted during times of high sea level, when terraces were eroded and alluviated. Some of these are evidently gravel-veneered, but only two terraces could be located at any cross-section using existing topographic maps, and they could not readily be tied to any of the recognized marine terraces.

A complex stress history could be unravelled by field study of the morphology of the Savannah River Valley. Because the most recent events have the strongest bearing on the matter of reservoir-induced seismicity, the present state of understanding of the Pleistocene is outlined here: When Pliocene time ended, sea level apparently stood at about the level of the modern 100 ft contour and about 40 miles from today's coast line. The Aiken-Louisville Plateau, the highest and most dissected coastal plain surface, was probably planed to that base-level, coincident with the Piedmont Pliocene peneplain. Its gradient of 8 ft/mile suggests antiquity, uplift and tilting since the modern Savannah River slopes 1 ft/mile at the same distance from the coast. The plateau may have been eroded considerably before the first interglacial submergence because the highest terrace, at elevation 270, has a very irregular shoreward outline.

Each glacial advance was accompanied by a fall of sea-level, and each interglacial, by a rise. But because of progressive epeirogenesis, each succeeding high stage cut a terrace lower than its predecessor.

These are:

Name	Elevation
Hazelhurst	270
Coharie	215
Sunderland	170
Wicomico	100
Penholoway	70
Talbot	42
Pamlico	25

In places prominent scarps separate these surfaces, such as the Surry Scarp shown in Figure 5. Above it is the Sunderland Terrace, and above the next higher, the Citronelle Scarp, lies the Coharie Terrace. These latter two (at least) swing parallel to the north bank of the Savannah River and extend to the Fall Line, suggesting that interglacial stages produced estuarine drowning of all river-mouths, as is the case today, the latest interglacial.

The sedimentary effects of a rising base level usually reaches far upstream. Channel aggradation and water-table rise took place in some cases, as indicated by terrace gravels adjacent to Clark Hill Reservoir. On the south Saluda River are gravels as much as 100 ft above modern river grade (Haselton, 1974), and similar temporary fills must have occured in the area of Richard B. Russell Dam. They are more likely to have occured during the early interglacials than later, when the sea had retreated because of uplift. The oldest gravel (100 ft) on the South Saluda is in an advanced state of weathering, and reworked gravel seen on the shore of Clark Hill Reservoir is

a residual of only the quartz gravels, all other rock types having disintegrated. The implied antiquity associates such river terraces with the earliest coastal terraces. In the vicinity of Richard B. Russell Reservoir, inspection of topographic maps provided suggestions of two terraces, one of which is continuous with two terraces at the Clark Hill Reservoir. Their ages or correlations with coastal features is unknown.

7a. At an arbitrary reference position about 10 miles upstream of the Richard B. Russell damsite, the Piedmont surface stands at elevation 575. The highest terrace is at about 505, the lowest at 395, and the modern river bed, 325. Stress changes can be computed using the stage-volume curve of Figure 1 and the assumption that the slopes developed similar to the present slopes so that the eroded volume is proportional to the depth of cutting. When the valley was 70 ft deep (575-505), its volume was 70/270 x 27% = 7% or 19 ft (average) eroded, reducing effective stresses by: $\Delta\sigma ez$ = -22 psi and $\Delta\sigma ex$ = -9 psi. The corresponding cooling effect was, on the average: $\Delta\sigma ex$ = -2 psi. The resulting uplift, 15.5 ft, reduced effective stress by: $\Delta\sigma ex$ = -5 psi. The falling water table, 70 ft in the valleys and about 20 ft on divides, provided an average fall of 45 ft for a change of effective stresses: $\Delta\sigma ez = \Delta\sigma ex$ = +19 psi.

7b. The second incision, to terrace level 395 ft, involved 180 ft of total erosion below the Piedmont surface (575 - 395). The volume was 180/270 x 27% = 18% or 49 ft average, for total changes of effective stress: $\Delta\sigma ez$ = -56 psi and $\Delta\sigma ex$ = -24 psi, and net changes: $\Delta\sigma ez$ = -34

psi and $\Delta\sigma ex$ = -15 psi. The cooling due to incision from the 575 to the 395 ft terrace level changed stress by: $\Delta\sigma ex$ = -6 psi and the net change: $\Delta\sigma ex$ = -4 psi. Uplift was 40 ft which altered stress by: $\Delta\sigma ex$ = -14 psi for a net change of: $\Delta\sigma ex$ = -9 psi. The falling water table, 180 ft in the valleys and about 50 ft on the divides averaged 115 ft for effective stress changes: $\Delta\sigma ez = \Delta\sigma ex$ = +50 psi which translate to net changes: $\Delta\sigma ez = \Delta\sigma ex$ = +31 psi.

7c. The complete incision and valley-cutting to today's configuration produced a total stress change of 73 ft average, for effective stress changes: $\Delta\sigma ez$ = -84 psi, $\Delta\sigma ex$ = -36 psi and net changes from the 395 ft terrace to the 325 ft stream level: $\Delta\sigma ez$ = -28 psi and $\Delta\sigma ex$ = -12 psi. The cooling due to 73 ft of erosion was: $\Delta\sigma ex$ = -9.5 psi producing a net effect of $\Delta\sigma ex$ = -3.5 psi. The total uplift of 60 ft would change stress by: $\Delta\sigma ex$ = -21 psi with a net effect of $\Delta\sigma ex$ = -7psi. Water table elevations have fallen from the Piedmont surface level by 250 ft at streams, and about 100 ft on divides, for an average potential change of 175 ft, changing stress by: $\Delta\sigma ez = \Delta\sigma ex$ = +76 psi and a net change of: $\Delta\sigma ez = \Delta\sigma ex$ = +26 psi.

8a. Stream alluviations indicated by gravel remnants were of uncertain depths. Assuming a fill of 100 ft of gravel in a canyon to illustrate what may have happened between incisions, it can be shown that its effect on total stress is far less than are the changes brought about by 100 ft of incision, because alluviation is restricted to the canyon bottom, like a dense reservoir.

If we assume the ancient topography to be similar to the

modern topography, but more subdued, it can be estimated that 100 ft of fill in the valley was like 8%, or 18 ft over the watershed. Allowing for its density, such loading changed effective stresses by: $\Delta\sigma ez$ = +16 psi and $\Delta\sigma ex$ = +7 psi. The corresponding heating is difficult to estimate, but is believed very small because the alluvial fill contains flowing groundwater at essentially the mean annual temperature. The subsidence would be 6.5 ft, producing stress changes of: $\Delta\sigma ex$ = +2 psi. The groundwater discharge levels would rise 100 ft, producing 50 ft potential change at depth: $\Delta\sigma ez$ = $\Delta\sigma ex$ = -22 psi. 8b. Subsequent removal of the alluvium would remove those transient loads.

An unusual feature of the Savannah River (Kilpatrick, 1964) is the apparent absence of channel fills that record, on most rivers, structural or sedimentological interruptions of bedrock incision, or steep tributaries. The present Savannah River gradient, about 2.7 ft/mile, is apparently steeper than required to transport the sediment carried. It is probably oversteepened by tectonic tilting.

The load that will be imposed by the full pool of Richard B. Russell Reservoir, at water surface elevation 474, is the sum of the deadweight and the pore pressure change, but no thermal effect nor isostatic subsidence is expected because the time span is too short. The reservoir volume, 1.9 x 10^6 acre-ft spread over the 0.5 x 10^6 acre watershed, is only a 4 ft load, changing effective stresses by: $\Delta\sigma ez$ = +2 psi, $\Delta\sigma ex$ = 1 psi. The ground-water discharge potential will be raised 125 ft (at the reference point), and the average po-

Table I - Summary of Effective Stress Changes (psi)

Step No.	$\Delta\sigma_{ez}$ (Vertical) Increments	Cumulative	$\Delta\sigma_{ex}$ (Horizontal) Increments	Cumulative	Age (Approximate) YBP
1		0		0	85 x 10^6 post mid-Cretaceous
2	-1422 +511	-911	-344 -609 -160 +511	-602	65 x 10^6 end Cretaceous
3	-1346 + 504	-1753	-327 -578 -152 +504	-1155	26 x 10^6 end Oligocene
4	-247 + 93	-1907	- 60 -106 - 28 + 93	-1256	7 x 10^6 end Miocene
5	(Seismicity?)				5 x 10^6 Pliocene
6a	+153 - 87	-1841	+43 +66 +26 -87	-1208	3 x 10^6 Pliocene
6b	-153 + 87	-1907	-43 -66 -26 +87	-1256	1.5 x 10^6 end Pliocene
7a	-22 +19	-1910	- 9 - 2 - 5 +19	-1253	1. x 10^6 Aftonian (?)
7b	-34 +31	-1913	-15 - 4 - 9 +31	-1250	500,000 Yarmouth (?)
8a	+16 -22	-1919	+ 7 + 2 -22	-1263	Illinoisan (?)
8b	-16 +22	-1913	- 7 - 2 +22	-1250	130,000
7c	-28 +26	-1915	-12 - 3 - 7 +26	-1246	10,000
9	+ 2 -27	-1940	+ 1 -27	-1272	Fill Reservoir, Future

tential change at depth will be raised about 62 ft, changing effective stresses by: $\Delta\sigma ez = \Delta\sigma ex = -27$ psi.

Figure 4 illustrates the changes of effective stresses most significant to the question of reservoir-induced seismicity. The Pleistocene history of river incision tended towards failure, i.e., the Mohr's circle of stresses shifted progressively towards the failure envelope; consequently, at least a modest level of seismicity due to fault slippage may have prevailed since Pliocene time when the alluvial cover was stripped. Intermittent valley alluviations probably stimulated greater seismicity, followed during river degradations, by diminished seismicity. The decreases of effective stresses predicted to result from reservoir filling are numerically more significant than the latest geomorphic changes. They indicate that conditions are appropriate for induced seismic enhancement. No threshhold of prior stress conditions exists.

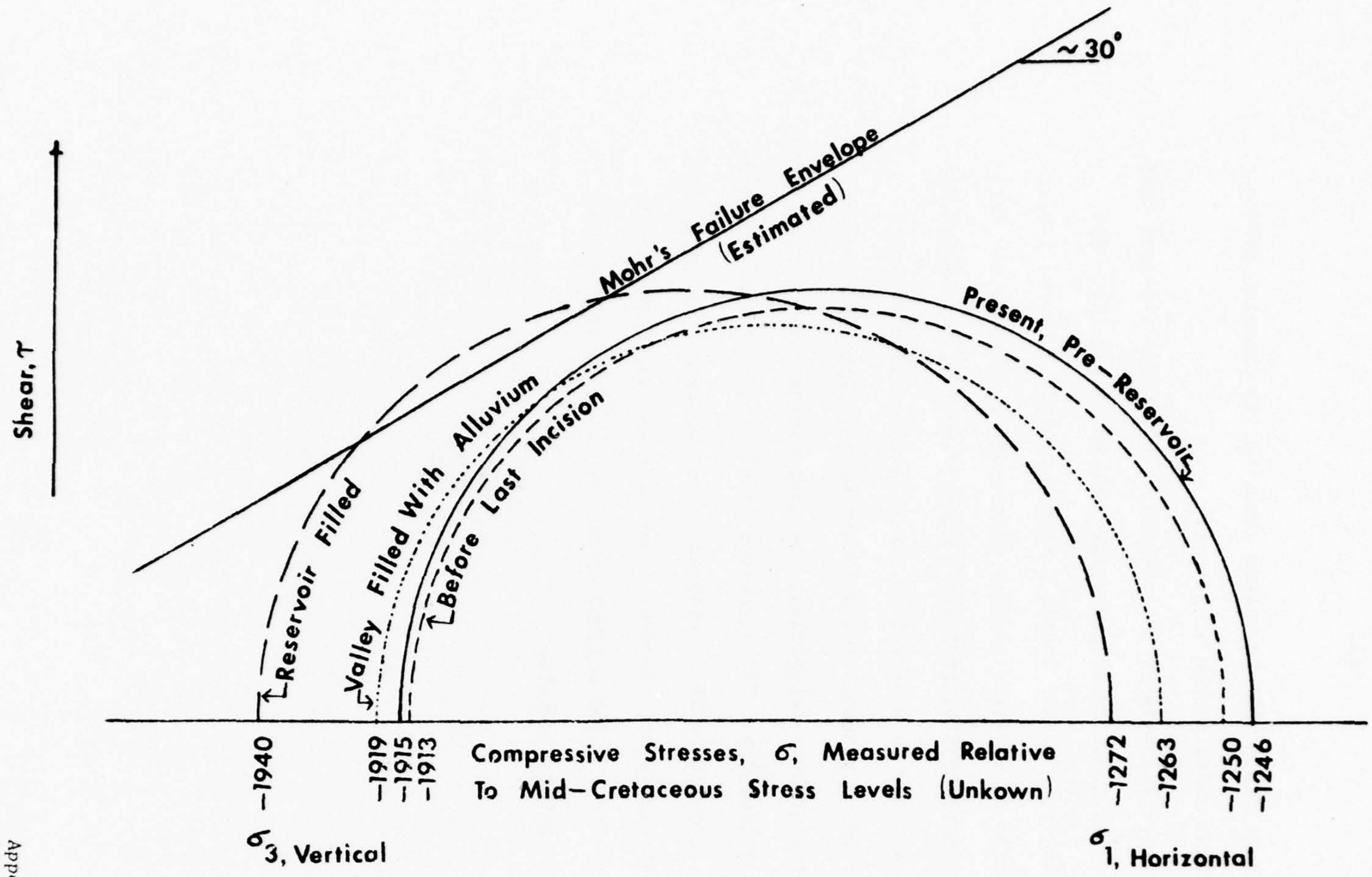


Figure 4. ILLUSTRATIVE ROCK STRESSES IN THE REGION OF THE R.B. RUSSELL DAM, WITH CHANGES DUE TO HISTORIC AND FUTURE LOADING.

CONCLUSIONS

1. Comparison of the proposed Richard B. Russell Reservoir with other Piedmont reservoirs does not provide clear-cut reasons to predict that the proposed one will be especially seismic, nor does it indicate why one (Hartwell) should be evidently aseismic, another (Clark Hill) weakly seismic or delayed in reservoir response, and a third (Jocassee) evidently produces swarms of low-magnitude (M<4) quakes in its immediate area.

2. Richard B. Russell Reservoir, like Clark Hill and Hartwell, will alter the state of effective stresses in the adjoining and underlying rock in a direction tending to foster failure by fault slippage under pre-existing tectonic stresses. The changes of stresses attributable to natural, pre-reservoir geomorphic events, such as Pleistocene river incision, have also been unfavorable; therefore, the natural seismicity is a logical consequence of the history of the region and the reservoir will tend to increase the local seismicity.

3. Experience with numerous seismogenic reservoirs suggests that shocks can be expected to occur with greater frequency, and at closer proximity to the reservoir than would have been the expectation derived from the history of naturally-occuring earthquakes in the region. There is scant evidence (except Koyna) that the maximum probable quake may exceed the expectation of natural events, nor is there reason to predict earthquake swarm activity.

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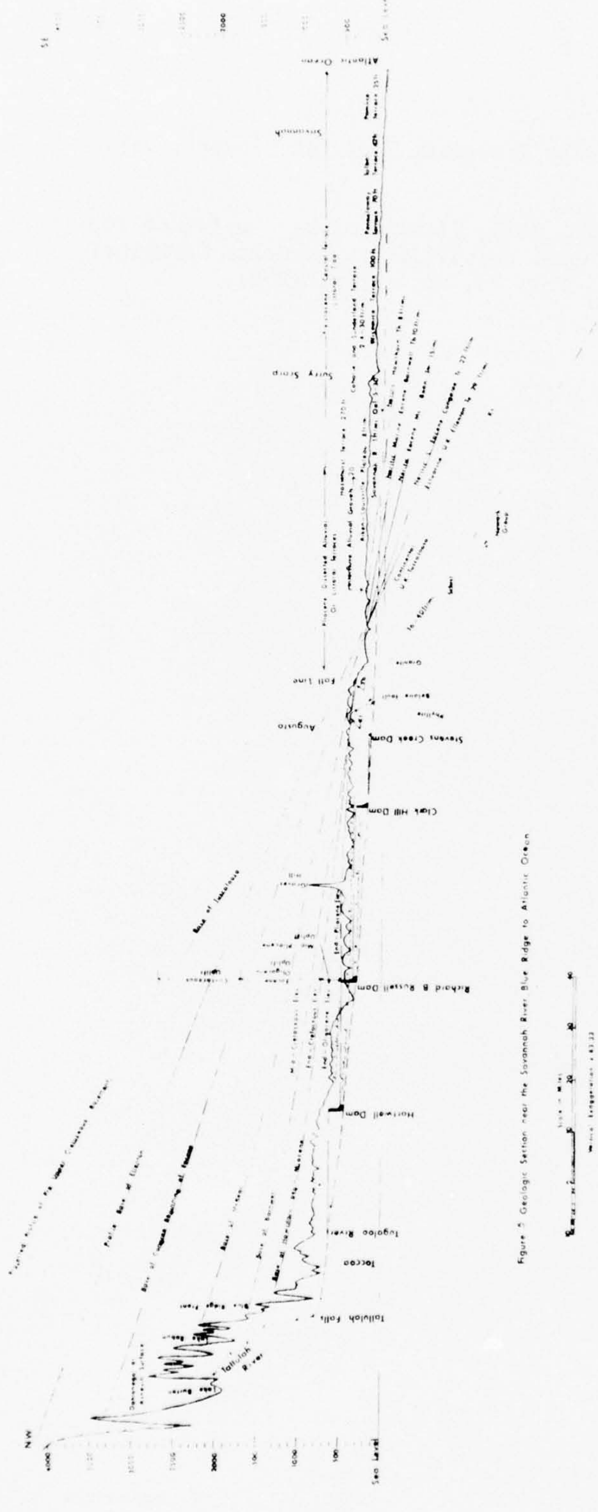

Figure 5 Geologic Section near the Savannah River Blue Ridge to Atlantic Ocean

SECTION F

CRITIQUE OF
INDUCED SEISMICITY AT RICHARD B. RUSSELL RESERVOIR

By Dr. David T. Snow

With Comments From Waterways Experiment Station

CRITIQUE OF INDUCED SEISMICITY AT RICHARD B. RUSSELL RESERVOIR

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DEPARTMENT OF THE ARMY
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IN REPLY REFER TO: WESSH

17 February 1977

MEMORANDUM FOR RECORD

SUBJECT: Comments on Report Entitled "Induced Seismicity at Richard B. Russell Reservoir" Submitted by Dr. David T. Snow to the Savannah District

1. Dr. Snow draws together, by complicated deductive processes, information from several disciplines to attempt a numerically-based assessment of the possibility of induced seismicity at the Richard B. Russell site. I am unable to accept his determination as being scientifically substantiated to the extent necessary to project an enhanced seismicity at the site, or indeed any change at all.

2. In his process, Dr. Snow calculates effective stress changes from an unknown stress condition said to exist 85 million years past. In his report he says: "There is some doubt about the magnitudes and direction of in situ principle (sic) stresses" (page 7, line 4). This is indeed the crux of the matter. The near-past seismic history of the site is a function of stress as it now exists, assuming slow changes with time. Since the concern is cited to be the change in effective stress, only the current state of stress and the influence of reservoir filling on the stress state need be considered (assuming that the current stresses may be defined reliably).

3. In the same light, it must be noted that regional increases in pore pressure must have already taken place due to the impoundment of reservoirs both up and immediately downstream. These do not appear to have altered the stresses at the site sufficiently to induce seismicity at the site. Hence, the magnitude of proposed stress change should incorporate the existing pore pressures, which tend to lower the incremental change attributed to the project reservoir.

4. Indeed, when the incremental stress change is put into proper focus by a comparison with stresses which might exist at depth under the reservoir (see Incl 1 to MFR by Don Banks dated 17 February 1977, subject as above), the stress change is relatively insignificant. If seismicity

were to be changed significantly due to this stress increment, the region would have to be existing at a stress level of incipient failure, which would tolerate no buildup of strain energy in the region due to a continuous stress relief, i.e. failure. One could argue that only small events could occur in this case, and that reservoir filling would be easily accommodated without a significant (damaging) event. Such an incipient failure condition might also be reflected in a high rate of micro-seismic activity in the area, before or after the filling of adjacent reservoirs, a condition not obviously apparent at the site. In this light I wonder if any worry at all need be expended related to stress changes of the order hypothesized. Referring to the author's figure 4, the change in maximum shear stress between the pre- and post-filling states is essentially zero, and the corresponding change in required strength (ϕ) to accommodate the changed stress condition is small, i.e. < 1 to 2 deg. Such orders are not within our ability to determine and would exist within the scatter of test data (although his assumed 30 deg may be low).

5. Figure 4, though intended to be illustrative, is misleading in that it shows a failure envelope to exist near the hypothetical stress circles. This is incorrect since stresses shown are stress changes from some unknown stress condition which might have existed 85 million years past, and the absolute position of current stresses on a plot of this nature is unknown. Hence, no relationship may be reasonably established between a possible failure condition for the material and a "change" of stress due to reservoir filling on this basis.

6. Dr. Snow is complimented for his effort to establish a conceptual framework by which possible seismicity might be examined. I do not feel that his concepts, however appropriate, are sufficient to support a conclusion regarding induced seismicity by quantitative means at this point in time.

7. I suggest that world-wide evidence indicates that induced seismicity is unusual, i.e., several hundred quiescent reservoirs versus about 30 with possible activity. Experience within the Piedmont would also support this argument; a necessary but not sufficient condition.

8. In summary, Dr. Snow's report does not serve to adequately substantiate conclusions regarding either the possibility of or lack of induced seismicity at the site and is not considered to be a useful document at this time. It represents an attempt to apply a largely unproven concept

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to a practical situation, unsuccessfully for practical purposes. Specific comments are attached (Incl 1).

1 Incl
as

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Engineer
Chief, Earthquake Engineering and Vibrations Division

CF:
Mr. Earl Titcomb, Savannah District
Dr. James Erwin, SAD
Mr. Paul Fisher, OCE

Appendix 1
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SPECIFIC COMMENTS

1. Page 5, line 5: What is seismic history? Has incidence or intensity increased? Negative or positive contribution to present assessment? Size of Russell Reservoir compared with "larger and deeper?"

2. Page 5, line 8: How true! This statement almost totally reflects on the present effort to assign ±25 psi changes in $\bar{\sigma}$ as being too fine an edge to hone.

3. Page 6, item (3): What is the basis for selection of Poisson's ratio = 0.3?

4. Page 7, line 1: What relative degree of seismicity is delineated by "a degree of?" Also, generalizing the existence of stresses near "critical for failure" requires more evidence than presented,

5. Page 7, line 4: There is indeed doubt regarding existing σ and orientation thereof which essentially renders later stress change calculation to be of no (quantitative) value, and possibly of little qualitative value. As pointed out by Don Banks, why guess at changes of σ over 85 million years when you don't know what the initial σ were to which these changes of stress should be applied. A better substantiation of the hypothesis would be to determine current in situ stresses, overcoring or whatever, and see what the reservoir does to these.

6. Page 7, line 9-19: Is this a strong argument?

7. Page 8, line 1: The spacial distribution of pore pressure increase is likely to be very site-dependent.

8. Page 8, line 14-16: Very tentative; I would say that balance of evidence (say several hundred reservoirs versus approximately 30) suggests induced seismicity to be unusual circumstance.

9. Page 8, last line: See statement regarding page 7, line 4.

10. Page 20, last paragraph, first four lines: Casts doubt on actual validity of study.

Incl 1 to Incl 2

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MEMORANDUM FOR RECORD

SUBJECT: Comments on Report Entitled "Induced Seismicity at Richard B. Russell Reservoir" Submitted by Dr. David T. Snow to the Savannah District

1. I have always been impressed by the deductive reasoning advanced by geologists in pursuing their studies. The reasoning embodies a great breadth of experience, careful observations, critiques, understanding of the important conclusions of previous and contemporary investigators, and most importantly a careful, well-documented logic that leads to substantiated, well-grounded conclusions. Perhaps the most overwhelming impression obtained by reading the subject report is that a conclusion was reached and references, either in the form of reports, personal communication, or by mathematical logic, were invoked whenever necessary or convenient, whether applicable or not, to lead to these conclusions. In particular (quoting from Conclusions) "Comparison of the proposed Richard B. Russell Reservoir with other Piedmont reservoirs does not provide clear-cut reasons to predict that the proposed one will be especially seismic..." (agreed that is the primary purpose of the detailed seismological study being pursued, but the question remains, what facts have been discovered by the present study to establish a reason to suspect the Richard B. Russell Reservoir will produce detrimental seismic activity?). (Again quoting from Conclusions) "Richard B. Russell Reservoir ...will alter the state of effective stresses in the adjoining and underlying rock (agreed) in a direction tending to foster failure by fault slippage under pre-existing tectonic stresses (to be proved). The changes of stresses attributable to natural...events...have also been unfavorable, therefore, the natural seismicity is a logical consequence of the history of the region and the reservoir will tend to increase the local seismicity (I don't believe this was substantiated by the study). (Again quoting from Conclusions) "There is scant evidence (except Koyna) that the maximum probable quake may exceed the expectation of natural events, nor is there reason to predict earthquake swarm activity." I believe the proper statement should be "No evidence was produced to indicate a maximum probable quake, induced from reservoir loading, will exceed the expectation...etc...." The references to Koyna Reservoir in the report show no relationship to the Richard B. Russell Reservoir.

V

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2. Perhaps, to me at least, the most difficult point of the report to accept is the method used to arrive at the change in stresses beneath the proposed reservoir.

3. In reference to illustrations A and B and the ensuing calculations, the following comments are offered: Invoking Archimedes' Law to obtain a relation between erosion or alluviation of material and the uplift or subsidence of a free floating body is correct in certain contexts such as the quoted case of an iceberg. My main question is, however, what is the analogy of an iceberg and basement rocks at Richard B. Russell? If the analogy is accepted, the law should be followed consistently. For example, why does the material in the crustal depth, D, exhibit one mass density below sea level and another above? Far more important, however, why was the analogy "stopped" and the theory of elasticity suddenly invoked? If h is the depth to a point beneath sea level, then the vertical stress at a point inside the "iceberg" is $\gamma_1 h_1 + \gamma_2(h)$ and at a point outside the "iceberg" is $\gamma_3(h)$. After erosion the vertical stress inside the "iceberg" is $\gamma_1 h_2 + \gamma_2(h)$ and at a point outside the "iceberg" is $\gamma_3(h)$. Since the law is for a body in a fluid, the horizontal stress, is $\gamma_3 h$ both within and without the "iceberg."

4. It seems to me that geologic considerations are certainly more complex for the area (for example, see chapters on Tectonic Evaluation and Geomorphic Evaluation) than implied by the use of Archimedes' Law. Certainly faulting, folding, orogeny, etc., have influenced and altered the stress changes in a far more complex manner than implied.

5. In reference to calculations summarized on Table I the following comments are offered. The calculational exercise must have been interesting, but what does exercise prove? No estimate is available concerning the state of stress predating the Cretaceous period. If such state of stress had been known and the area acted like an "iceberg" then calculation of the changes in stress to arrive at the present state or stress might have some meaning. In the absence of such knowledge it would be more appropriate to estimate the present state of stress. Certainly this estimation is difficult and probably impossible, but clouding the issue with a set of calculations showing stress changes from Cretaceous time is not desirable.

6. The point of the objection is illustrated as follows: Let us, for the sake of argument, calculate the effective stress at a point 10,000 ft beneath the reservoir.

Assume $\gamma_{sat} = 165\ lb/ft^3$

$\gamma_{water} = 65\ lb/ft^3$

Then $\sigma_v = (10{,}000)\ (165-65)/144 = 6950$ psi

Assume $K_o = 0.5$

Then $\sigma_h = 3475$ psi

The change in stresses, as estimated by Snow is

$\sigma_v = 25$ psi net decrease

$\sigma_h = 26$ psi net decrease

When these stresses are plotted on the attached figure (Incl 1) a different picture results than that portrayed on Figure 4 of the subject report. It is true that the net decrease in effective stress causes a shift in the Mohr's circle toward an assumed but unsubstantiated failure envelope defined by an angle of internal friction of Ø = 30 deg. but in no way does the exercise imply that induced seismicity will be a consequence of the filling of the Richard B. Russell Reservoir.

7. Figure 4 is completely misleading and should not be used in any publication concerning Richard B. Russell Dam and Reservoir.

Don Ban

1 Incl
as

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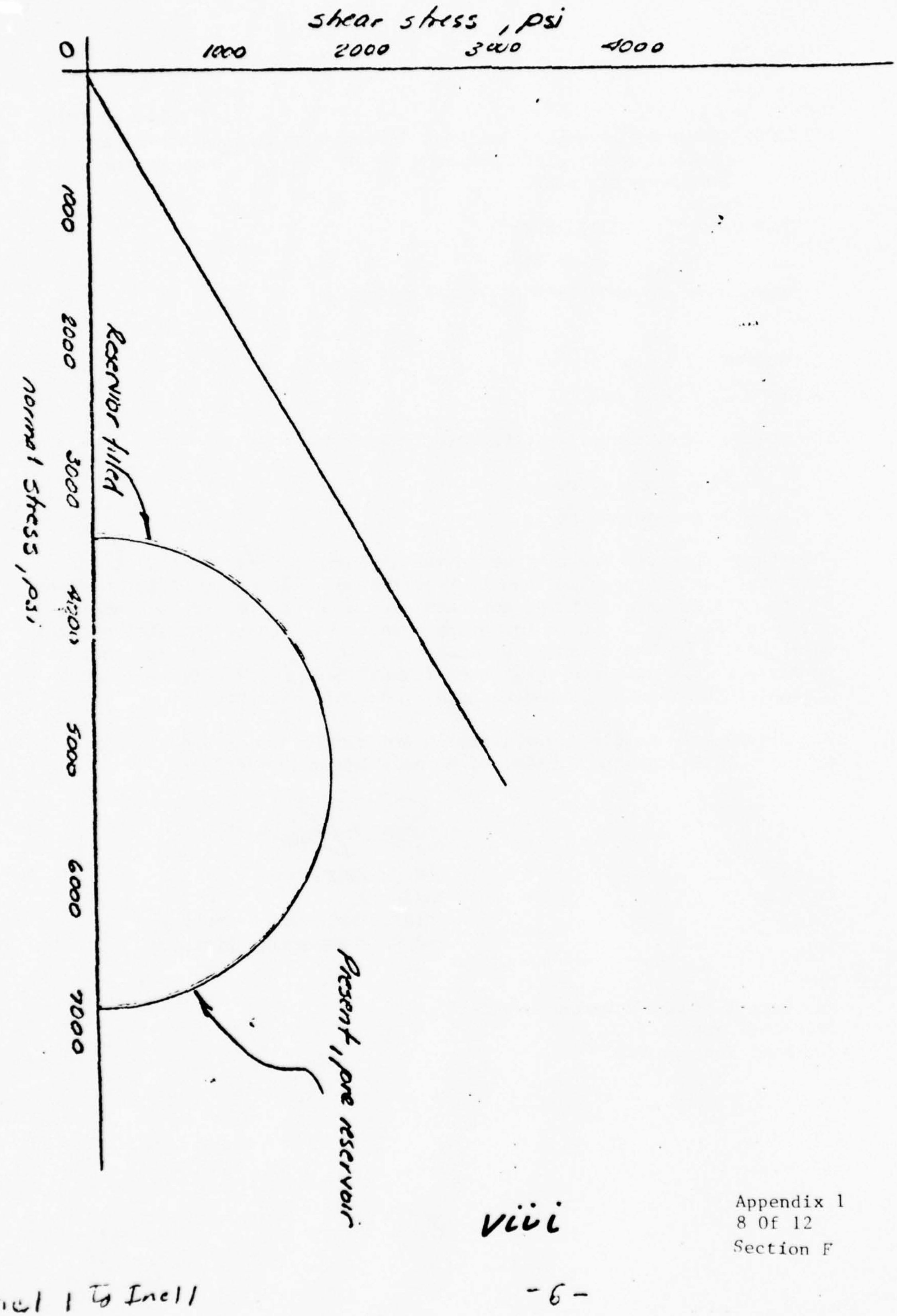

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Appendix 1
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Section F

Incl 1 To Incl 1

DEPARTMENT OF THE ARMY
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17 February 1977

MEMORANDUM FOR RECORD

SUBJECT: Comments on Report Entitled "Induced Seismicity at Richard B. Russell Reservoir" Submitted by Dr. David T. Snow to the Savannah District

1. Dr. Snow's model is that of a cumulative relief of effective stresses produced by removal of the geological section from the Cretaceous (approximately 100 million years ago) to the present. The stress changes are those resulting from erosion, temperature change, and isotatic adjustment. Dr. Snow states that these factors produce a decrease of vertical stress in excess of the decrease in horizontal stress. The small stress changes resulting from the above processes are superimposed on the regional tectonic stresses. Unspecified, high, horizontal compression is assumed.

2. Dr. Snow postulates that an increase in pressure from weight in a reservoir decreases effective stresses in rocks. He postulates also that these decreases more than offset the increase of effective stresses resulting from deadweight of water, an assumption that is not supported in his analysis.

3. Along a fault, a decrease in effective stresses in rocks reduces the resistance of the fault to slippage. If the reduction is below a critical level, movement is triggered and an earthquake is produced. Dr. Snow states that reservoir-induced changes in effective stress extend to about 3 km below the surface and several km laterally from the reservoir.

4. If I understand Dr. Snow's paper correctly, he postulates a cumulative residual effect, in terms of stresses, for all strata removed over a period of 100 million years, that is, dating back to the upper Cretaceous. Dr. Snow cites 2,270 ft of uplift and erosion at the Russell site since the mid-Cretaceous and that the topography is now only 425 ft lower than formerly. Not cited is the horizontal motion that this portion of the crustal plate underwent in the same period of time. Its movement was some thousands of miles. In addition to major compressive effects, there were periods of relaxation. In the Triassic, grabens and basins were formed and were filled with sediments. These processes may

have induced internal changes in the section that affect density and load as great as, or possibly more than, the cited effects of erosion. In any event, an analysis should begin, not with postulations of past geologic history, but with assumptions of stress for the present conditions only and then allow for the addition of a reservoir.

5. The hinge line that Dr. Snow places at the boundary of the Coastal Plain is also a simplification, and perhaps too great a simplification. That hinge line forms a fixed demarcation that encompasses the entire geological section. Hinge lines move through time. As a basin develops, its hinge line typically moves outward in order to allow for the enlargement of the basin. Thus the postulations based on a fixed hinge line may be subject to other interpretations.

6. Dr. Snow's model assumes that, in the Russell area, there are only compressional forces, those that produce earthquakes by activating thrust faults. Seismological studies of microearthquakes (earthquakes so small that they are recorded only by instruments) near the Clark Hill Reservoir show exactly the opposite. The microearthquakes were produced by normal faults.

7. Dr. Snow observed that there is a disparity in the occurrence of earthquakes at the existing reservoirs along the Savannah River. The Hartwell and Keowee Reservoirs have no microearthquakes; however, microearthquakes have occurred at the Clark Hill Reservoir.

8. There have been two felt earthquakes in the Clark Hill area. The first was in 1875, long before there was a reservoir. The second was in 1974 after the Clark Hill reservoir had been in operation for 21 years. Because of the time of occurrence of the first earthquake and the long time interval between filling of the reservoir and the occurrence of the second earthquake, both earthquakes must be interpreted as having occurred independently of the reservoir. They were produced by regional tectonism. The microearthquakes that occurred following the 1974 earthquake at Clark Hill have the following characteristics: they are predominantly shallow, only a few kilometers below the surface, and they do not define any single fault, rather, they define an elliptical zone of faults. The forces that produced the microearthquakes were interpreted by Talwani, using the seismic records, as tensional. In combination, the microearthquakes form a seismic "hot spot."

9. Geologically, the general area of the Clark Hill and Russell Reservoirs is composed of northeast to southwest trending bands or zones of varying lithologies. The seismic hot spot at Clark Hill is approximately at a boundary between two lithologic zones and the long axis of the hot spot parallels the boundary.

10. Compressional and tensional forces may work together in the Piedmont. One can visualize a situation, akin to that of a glacier, where there is flow at depth through a process of plastic deformation in which the forces are compressional. Near the surface, the glacier is shattered with fissures and crevasses representing conditions of tension. The contrast is there because motion is not uniform through the section. Similarly, lateral motions in zones of rocks in the Piedmont may be taken up by a sort of plastic flow. Adjacent rocks with dissimilar properties of deformation may not deform in concert. The nondeforming material may then behave as a brittle substance and shatter, producing microearthquakes within a narrow, shallow zone akin to the crevasse areas of a glacier. At depth, the rock may deform plastically and not be active seismically.

11. A model, similar to that described above, would explain the hot spot of seismicity at Clark Hill. It would explain the shallow, isolated character of the hot spot and the absence of hot spots at other areas, notably at the nearby Hartwell Reservoir.

12. If the above concept of a hot spot is valid, the model is self-limiting with regard to the maximum earthquake that can be generated in a hot spot. The dispersal of movement along a zone of shallow faults presupposes a dispersal of the energy available for earthquakes, therefore, there will not be a buildup to a very large earthquake.

13. The local situation described above, or other possible interpretations, were not addressed by Dr. Snow and perhaps cannot be addressed using his method. Dr. Snow's analysis for a compressional condition showed that earthquakes would be induced. For a tensional situation, earthquakes should be inhibited. From this limited standpoint, the earthquakes at Clark Hill are the opposite of what would be expected from the interpretation of Dr. Snow.

14. Dr. Snow concludes that, "There is scant evidence (except Koyna) that the maximum probable quake may exceed the expectation of natural events...." On the basis of Dr. Snow's report, there is no evidence rather than "scant." A maximum earthquake for the Richard B. Russell site was taken to be magnitude 5.5. This value was endorsed by the seismological and geological consultants to this project, Drs. L. T. Long, Pradeep Talwani, O. W. Nuttli, and D. B. Slemmons. Dr. Snow was also a member of this group and agreed to the same maximum value for the earthquake.

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15. Dr. Snow's report was commissioned with the expectation that he would use the most advanced art to review and speculate upon the processes affecting induced seismicity in this portion of the Piedmont. Unfortunately, his report is technically deficient.

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SECTION G

REBUTAL

Responses to Comments of Reviewers of Induced Seismicity
Richard B Russell Reservoir

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Responses to Comments of Reviewers

of Induced Seismicity

Richard B. Russell Reservoir

by David T. Snow

. Nineteenth-century geologists deduced from the paleontologic record of periodic, widespread annihilation of species that there have been distinct tectonic events, world-wide catastrophes that folded, faulted and uptilted the sediments and built mountains. It appeared from the thick sequences of basin sediments, with continuously-evolving organisms, that tectonism was absent between orogenic events. Until very recently, modern geologists have retained the corollary notion that the stresses necessary to produce faults or folds have likewise been periodic. Laboratory evidence that rocks creep during geologic time suggested that the mountain-building stresses must die out soon after each "revolution".

If there is nothing else that proven cases of induced seismicity have taught us, it is the fallacy of the old notions: high stresses persist long after the failure events. In Colorado, increased pore pressures of the order of 1000 psi have been sufficient to cause earthquakes at Denver and Rangely, releasing elastic energy attributable only to "tectonic" stresses that have not produced significant structures since the Cretaceous Laramide "revolution". Similar statements can be made for reservoirs associated with earthquake swarms and devastating earthquakes equal to the greatest natural magnitudes experienced (Kremasta, Greece; Bileča, Yugoslavia; Lake Mead, Nevada) or in some cases, greater magnitudes than ever (Koyna, India; Kariba,

Rhodesia). In some cases, the reservoir-induced quakes were produced in areas thought to be aseismic, lacking active faulting, as at Kariba and Koyna. In most of these cases, including Denver, Kremasta, Koyna, Kariba and Bileča, prior earthquakes, however infrequent, did occur, attesting to sufficient stress for failure, at least locally. This lead the writer (1968b),*to conclude that the most likely state of stress in any region of earthquakes or recent faulting is of a magnitude critical to failure on some fault(s) present, i.e. that stress is commonly governed mainly by strength, a function of depth. Whereas orientations of pre-failed slippage surfaces must be significant in some places, such ancient complexly faulted rocks as the Precambrian of the Colorado Front Range have such diverse fault orientations that one can safely assume that for large regions, a fault at the critical orientation exists. Particularly where erosion in the late geologic history has reduced confinement, the stresses have had to be relieved by earthquakes, so that the mass has remained near-critical, thus prone to failure upon decrease of effective stresses, such as reservoir filling or injection wells produce.

The above theory, perhaps unprovable, is yet more palatable than the old notion that earthquakes are capricious phenomena beyond our ken. In a general way, the earthquake release of stress, the resulting fault slip directions and regional crustal

*References are found in the subject report on R.B. Russell Reservoir, otherwise, new references are listed following this paper.

deformation taking place must all be consistingly related to the state of stress. Nowhere can one find thrust faulting adjacent to contemporary faulting, or a change of such character with depth involving an exchange of direction of σ_1 and σ_3. However, normal faulting and wrench faulting co-exist in the Basin and Range where σ_1 and σ_2 are equal along vertical NNE-striking planes.

The above does not preclude the existence of rock volumes bounded by faults that have failed or that are critical for failure, within which stresses are below the critical levels. In such volumes, measuring meters, kilometers or even hundreds of kilometers, it may require large changes of pore pressure to produce failure, because the stress in such a strong inclusion is limited by the strength on bounding faults. Within present capabilities, no amount of field geology is going to be adequate to define the volume boundaries or the magnitude of a safety threshold that might exist. Rather, it is best to assume a thin margin, treating each circumstance conservatively.

Would we have to say, then, that all reservoirs being planned are potentially seismic, since they all must raise basement pore-pressures, locally, at least? No, that is not correct. There are regions of geologically recent alluviation, such as the SE portion of the Basin and Range, where seismicity is rare, and deep basin alluviation has increased confinement on faults dipping beneath them. Further, there are circumstances of hydrologic isolation, where a reservoir will add to effective stress. If intervening confining beds and/or the basement daylights elsewhere, pore pressures will not be raised. Thus each site deserves scrutiny.

These notions have been expounded by the writer in prior publications (1972). There is no pretence of a complete theory, satisfying all our needs. Rather, continued attempts to understand seismicity under given circumstances, by people of divergent background and inclinations, is especially important for the study of induced seismicity because there are doubtless unrecognized variables and effects that bear on the prediction process. Empiricism will never suffice. No agency is able to shut off inquiry into the subject, but the Corps can stimulate or postpone attainment of design-worthy methods according to its treatment of such reports as the R.B. Russell evaluation. Criticism can be constructive.

The following paragraphs refer, by number, to paragraphs of the February 17, 1977 comments of Mr. Don C. Banks.

1. The facts discovered by the study were summarized in the statement, quoted from the conclusions, namely, "Richard B. Russell Reservoir --- will alter the state of effective stresses --- in a direction tending to foster failure ---". Proof was offered (Snow, 1972) that in steady-state, a reservoir on a homogenious porous medium would decrease effective stresses, and that such a change is essential for all stress environments; normal, wrench or thrust-fault. An infinitely-extensive reservoir of uniform depth would increase total vertical stress by the same amount as it increases pore pressure, but horizontal effective stress decreases in that case. Filling a canyon reservoir, like a well in continuity with its formations, does not appreciably increase total stresses in low-porosity basement rocks, but both effective stresses decrease by the amount of

pore-pressure rise in the environs. All reservoir configurations lie between these two extremes.

Since the Cretaceous, gradually-decreasing effective stresses over geologic time were demonstrated to have occurred at the R.B. Russell Reservoir area. On page 43 of the report is a description of Pleistocene effects shown in Figure 4 that tended to drive stresses towards failure. The greater decreases of σ_1 and σ_3 attributable to the mid-Cretaceous to Pleistocene (6b) history, also tended toward failure during most of that period, as noted in conclusion No. 2.

Continuing decreased stresses in the weakened crust are implied by the erosional unloading, consequently retaining criticallity and seismicity because thrust faulting was active early in that time span.

In the Mohr diagram, the absolute stress magnitude is unspecified because it is unknown; only changes are significant. The changes are presumed to be the same at all depths, whereas the magnitudes increase with depth in a way that maintains the circle of stresses near-tangent to the failure envelope. This is the working assumption previously stated: stresses at all levels approach failure if current or recent earthquakes or other evidence of deformation by brittle failure are in evidence.

Thus the report did substantiate the conclusion that the natural seismicity is a logical consequence of the history of the region, and that the reservoir will tend to increase the local seismicity. What the report did not substantiate is the theory. Any reader should have a healthy skepticism for a mechanical model, however logical, whose real-world counterpart

cannot yet be proved to exist. It will be a multi-million dollar project to prove the theory of the mechanism of induced seismicity, involving insitu strength tests and numerous deep piezometers and stress meters at great depths below a filling reservoir. Until then, prediction has to remain an art.

The theory suggested is at best qualitative, resulting in a fail/no fail conclusion. It says nothing about the size of the surface that fails, the displacemnt upon it, nor the resulting earthquake magnitude. For such important predictions, only our experiences at seismic reservoirs pertains: in some cases, filling a reservoir has been followed by an anomolous swarm of quakes in the immediate vicinity. The induced quakes are equal to, or greater than recorded natural events in the region. The Koyna quake of December 10, 1967, exceeded anything occurring in peninsula India in over 600 years of history. The induced quakes at Kariba were greater than ever experienced in the Zambezi Trough, but not greater than have been recorded in other parts of the African Rift system. The Hsinfengkiang (China), and Kremasta quakes have probably been equal to the greatest natural events. In most such cases, instrumental pre-reservoir records are inadequate for quantitative evaluation.

The Board of Consultants for seismicity evaluation of Richard B. Russell Reservoir adopted a design quake of magnitude 5.5, equivalent to the maximum recorded historical Piedmont quake, translated to the reservoir site. The near-field vibrational spectrum imposes accelerations of 0.5 g on the R.B. Russell structures, far greater than the design shaking (0.15 to 0.20 g) included in any previous Piedmont designs,

including several nuclear reactors. The writer endorsed the M = 5.5 quake as conservative and properly prudent, in view of the unfavorable change of seismic conditions that will be produced by the R.B. Russell Reservoir: the maximum historical Piedmont quake could be translated in place and time to the reservoir site. The writer does not find adequate reason for invoking a greater induced quake at the site, e.g., a Charleston quake of magnitude $7^{\pm}$ is deemed unlikely as a response to reservoir loading. Unfortunately, the theory advanced is inadequate for that purpose and the empirical approach is inconclusive. Only Koyna has generated a quake in excess of the natural maximum experience. Neither of the adjacent reservoirs, Clark Hill and Hartwell, have produced anything unusual in the Piedmont, nor have they produced the usual prompt swarm activity the way Jocassee Reservoir has done. It may be true that Clark Hill has influenced seismicity by causing the August 2, 1974 quake to take place closer in time and place than would naturally have happened. Conclusion 3 states that idea succinctly.

2. Mr. Banks' review does not specify which of the methods used to compute stress changes are unacceptable to him, so I can address only those mentioned in subsequent paragraphs.

3. The applicability of isostacy to basement rocks at the Richard B. Russell area is questioned. The fact that the crust is continuous, rather than composed of discrete blocks, does cloud the picture, though it doesn't change the physics of the uplift-subsidence phenomenon. One density above sea level, and another density below sea level is an objection well

taken, and corrected in the following replacement page for illustration A. The effect is a minor change (1%) of coefficients, not enough of a change to warrent altering the rest of the report.

The theory of isostatic rebound that I have developed is in accord with the theory of isostatic compensation advanced by Sir George Bidell Airy in 1955, namely, "that blocks of the earth's crust are floating in a relatively dense plastic material, usually called magma or sima. The excess of mass corresponding to high blocks is compensated for by a displacement of the denser plastic magma...." (Jakosky, 1950, p. 261).

When uplift of one portion of the continuous crust occurs relative to a subsiding adjacent part, the motions must, on the average, be radial to the earth. Thus a tangential extension accompanies uplift, and vice-versa. Elasticity is invoked to convert the strain to stress. This approach was suggested by Haxby and Turcotte (1976), and developed by the writer in a lecture at WES on April 28, 1976. The derivation is shown on Illustration A, attached.

4. This comment reflects possible problems in setting geologic events clearly in their chronology. The uplift and subsidence events deduced from the Coastal Plain stratigraphy were all post-Late Cretaceous, whereas the Paleozoic and Mesozoic structural events, such as faulting, folding, orogeny, etc. mentioned in Banks' review all preceeded the Tertiary uplift events. As pointed out on page 18, thrust-faulting has persisted at least until late-Eocene time. Stresses may have remained so oriented until the present, as suggested by stress

measurements throughout eastern U.S.A. Until Recent or Late-Tertiary faults other than thrust faults are discovered, it is deemed mechanically inconsistent with the facts to presume that there has been a change of stress configuration since the Late Eocene. To be sure, at any instant, an elastically anisotropic medium, inhomogeneous and cut by various failure surfaces, does not have within it a homogeneous stress field. However, if does possess a degree of consistency; the major and minor compression directions are not likely to reverse, and any other important deviations from the average stress orientations are apt to be local. It is inconceivable that stresses are capricious in place and time. They must make mechanical sense.

5. The question posed in paragraph 5 has been answered, namely, that stresses at the time of latest faulting were critical, they have changed adversely since then, probably resulting in continued stress release, so they are likely to be critical for failure now, at least in some places that govern the stress field. Any adverse change, such as a rise of pore pressure, can induce earthquakes if the change takes place in a critical place. There is no hope or need for absolute measures of stress, either now or in Late Cretaceous. If varies with depth anyway. The strength we know only in a general way, like a $30^{0\pm}$ envelope. To be sure, better failure criteria are attainable, but no one is getting such data for hypocentral depths.

An estimate of the present state of stress can be made, but at vastly great cost than was entailed in this brief study;

Haimson did deep hydrofrac stress measurements at Rangely to show that the water-flood experiment did alter effective stresses so as to induce or shut off earthquakes at will. Such work may become standard for proposed reservoirs, but the writer believes these may fail because most mildly seismic areas will prove to be critically stressed, and then how do we explain aseismic reservoirs? Better, more comprehensive theory is needed, not measurments of uninterpretable stresses, whose precision is inadequate to the task of predicting failure in a medium whose strengh properties are only approximately known.

6. The calulations shown in item 6 may pertain to shallow soils and to rare recently-deposited rocks. The Black Hills of South Dakota give an elastic, gravity field. Elsewhere, in eastern U.S. and much of the world, σ_1 is horizontal. Even in the Basin Range Province, σ_1 and σ_2 are equal, and σ_3 is horizontal. Mr. Banks has assumed $K_0 = 0.5$ or $\nu = 0.33$ and neglected the observed tectonic component, as is necessary for thrust faulting. Presently σ_1 is most likely to be horizontal still, in response to base shear of a westward-flowing mantle current rafting North America westward away from the Atlantic Rift. Until plate motion changes, it probable will remain so directed. Plotting gravity-induced stresses only will naturally indicate no possible failure, but that is not how it is today on the eastern seaboard. The small changes of stress to be caused by Richard B. Russell Reservoir would be harmless under a gravity stress field, but the line of reasoning proposed in this study recommends the scaleless Figure 4 as most representative of what exists at all places and depths, and shows how the induced

and historical stress changes are likely to influence stability.

The following paragraphs are in response to Dr. McLean's review.

1. This is a sweeping rejection of the numerical approach to the assessment of induced seismicity, on the grounds that the theory is unsubstanciated. Unfortunately, proof will entail field testing of stresses at depths currently accessable only by hydrofracing techniques, at costs that would run to millions. The theory is not sufficiently advanced to warrent it, because it remains incomplete: badly needed is a notion that may ultimately be translated into predicted quake magnitudes; until then, the theory only goes so far as to suggest whether or not failure by fault slippage may be expected. A first step in theory substanciation should be the installation of a deep(2-km) piezometer to record the pore pressure transient that follows filling of some new, large reservior. This would be to substanciate that pore pressure transients reach significant depths.

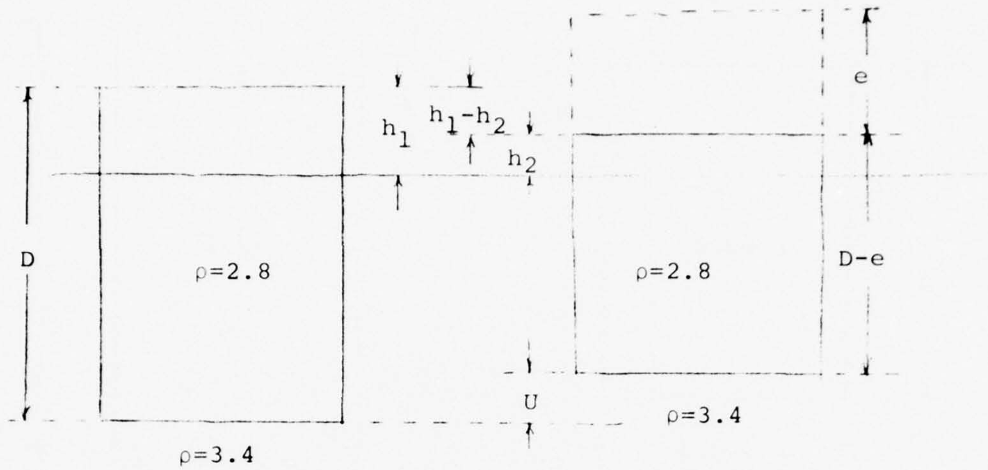
At least a large part of the theory will be vindicated in time. For example, the writer observed in 1968 that the coincidence of normal faulting and wrench faulting in the Dixie Valley quake site could only be possible if $\sigma_1 = \sigma_2$ = overburden at all crustal depths, and σ_3 is northwesterly. In 1970, a Colorado School of Mines graduate student, John Ege, commenced a program of stress measurement using overcoring and hydrofracing in seven tunnels in Ranier Mesa, Nevada Test Site. This year, Ege finished his dissertation, proving that the stress state is just as anticipated, and that stress levels are as close to sliding failure on pre-existing faults as precision of stress

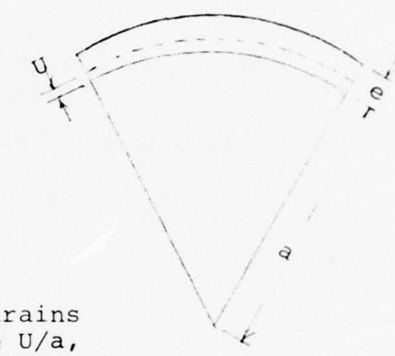
and strength measures can tell. The stresses are limited by the pattern of pre-existing faults.

2. Dr. McLean states the crux of the matter is the uncertainty about the current state of stress. It is not the crux at all; one may assume a stress condition for thrust-faulting (σ_3 vertical) or for wrench-faulting (σ_2 vertical) or in most cases (dependent on ν and ϕ) for normal faulting (σ_1 vertical). Given a late histroy of seismicity, decreases of effective stress drive the Mohr circle towards failure in all three cases. Maintenance of critici llty, by unloading, or by raising the water table in the pre-reservoir history, is usually going to be sufficient to predict enhanced seismicity when the reservoir is filled. The predication, though rational, may prove false in given localities because there may be undisclosed variables operating to prevent failure, e.g. the reservoir may overlie rock bounded by weak faults zones, between which the boundary-limited stresses are subcritical for failure.

If it is concluded, as have the reviewers, that the present-day stress alone has relivance, and thus the history of stress is insignificant, the only apparent approach to prediction is measurement of stress, strength and hydraulic potential. At this moment, inadequate precision seems an insurmountable obstacle to success. Perhaps methods of measurement can be improved. Because of their great expense an economical search for independent evidence of stress, stress changes or criticallity should preceed a measurement program costing millions, and tests should be interpretated in their historical-tectonic context. The subject report on Richard B. Russell Reservoir has attempted

Illustration A





Equating the mass of the columns, buoyed by the mantle:

$$2.8D = 2.8(D-e) + 3.4U$$
$$3.4U = 2.8e$$
$$U = .82e$$
$$e = 1.2U$$

The change of elevation:

$$h_2-h_1 = U-e = -.18U$$

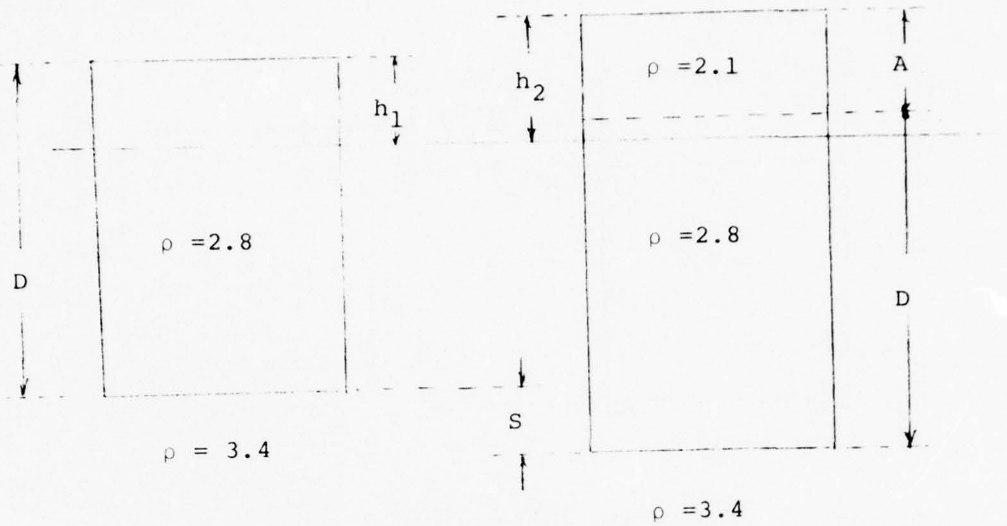
Both the vertical and circumferential strains produced by vertical (radial) uplift are U/a, a being the radius of the earth. Applying Hook's Law for uplift alone, $\Delta\sigma_y=0$ & $\Delta\sigma_x=\Delta\sigma_z$

$$\varepsilon_x = \frac{\nu-1}{E}\,\Delta\sigma_x$$

$$\Delta\sigma_x = -\frac{E}{1-\nu}\,\frac{U}{a}$$

$$\Delta\sigma_x = -\frac{5.\ X\ 10^6}{0.7}\,\frac{U}{2.09\ X\ 10^7} = .34U \text{ psi, where uplift is in ft.}$$

Illustration B



$$2.8D + 3.4S = 2.8D + 2.1A$$
$$S = .62A$$

If $S>0$ is a known subsidence, in ft,

$$\Delta\sigma_x = .34S \text{ psi.}$$

to do this from a meager, remote data base, such as stress at Jocassee Reservoir, 100 miles away.

3. The point has already been made, by Stanley Johnson, that Hartwell and Clark Hill Reservoirsconstitute ideal prototype-scale tests which have proved negative in respect to induced seismicity. The subject report, in addition, notes the apparent seismicity induced by Lake Jocassee and the lack of it at Keowee. It is clearly prudent to seek geologic reasons for such differences, if the behavior of R.B. Russell is in question. Is 75% unlikely an adequate measure?

Basement pore pressures have been raised by the neighboring reservoirs, up-and-downstream of Richard B. Russell, but the increase due to those reservoirs acting in the vicinity of the intermediate location must have been nil because of remoteness (Russell occupies 37 miles of the Savannah River) and especially because of anisotropy; pore pressures propagate much farther along strike than up-and-downstream.

4. Part of item 4 has been answered in response to Mr. Banks'comments. Indeed, the changes of effective stress are minute and in many places, such changes are probably insignificant, producing no seismicity because greater thresholds would have to be overcome. In other places or after other geologic events that similarly change stresses, the threshold can be so low that modest reservoirs can induce failure. Just how failure is produced depends upon the detailed behavoir of fault zones, including dilatational effective stress changes, stick-slip effects that locally alter the threshold that must be overcome for renewed failure to take place. It is clearly not an

infinitesimal process that would produce only microearthquakes. No comfort can be taken from the realization that reservoir-induced stress changes are so small that they can hardly be measured. Such changes have released huge stores of elastic energy at Kremasta, Kariba, Koyna and others, and we must deal with such minute changes.

In the years since 1968, when papers concerned with the Denver earthquakes first came to attention, many seismologits have become well-versed in elementary rock mechanics. The converse is less true: geologists have not been as quick to learn pertinent seismology. Even at the first important conference on induced seismicity held in 1972 at the Royal Society, most seismologists could not understand the equivalent of Figure 4, believing erroneously that shear stress is the criterion of rock failure. We cannot communicate in this business without Mohr's theory.

With respect to variations of strength, within which the estimated changes portrayed by Figure 4 can operate without failure, no ϕ-angle can be computed. The changes themselves are absolute, the same at all levels, but because the point of tangency is at higher stresses for greater depths, the corresponding angular change diminishes. The observation in paragraph 4 is moot.

5. McLean objects to the fundemental premise of the evaluation; as a segment of continental crust is shaved thinner by erosion, stresses would rise but for the strength limitations of ubiquitous faults. Unless a major change takes place in mantle circulations, or there is a shift of the portion of that

segment upon the mantle, diminishing strength as the crust grows thinner assures criticallity and continued seismicity. No absolute state of stress at any depth is needed to pursue the evolution of the rock beneath a reservoir; only the changes, and in normal-fault cases, the friction angle. The reader is referred to the author's 1972 publication.

Insofar as the writer has taken over 10 years to become convinced of the soundness of the notions involved, it comes as no suprise that a brief inspection may not suffice to be convincing. The conscientious reader cannot easilly rest when it is pointed out that there are things misunderstood upon first inspection. Full cooperation is always available if requested. The writer stands to benefit, as well.

6. Further comment on paragraphs 6 and 8 would be a reminder that the report made no firm assurance, offered no proof that the Richard B. Russell Reservoir would produce a damaging quake, though it may. All it said is that conditions are ripe for induced seismicity, so cautious design is approprate. The decision of the Board of Consultants to approve a near-field spectrum for the dam is an approprately prudent result of the findings.

7. There are several reservoirs associated in time and place with such swarms and unusual high-magnitude events as to leave no doubt in some minds that a relationship exists. The Corps of Engineers cannot afford to rest on the rareity of such reservoirs. What, for instance, was the cause of the Charleston quake? Was it late-Pleistocene coastal submergence that triggered it? An aftershock (?) studied by Tarr(1976) was a thrust-faulting

event. Whatever the stress configuration may have been in 1886, the same configuration must still prevail. Because a stress field must be continuous in sense though not uniform in direction throughout even an inhomogeneous elastic basement, the same stress field is likely to exist in the Piedmont. We have no answer, except a weak body of statistics on reservoirs, to the question, "What is to prevent another Koyna-like major quake?"

Dr. McLean has enumerated a page of specific comments, to which responses are made below:

Item I: The question is unclear to the writer, but if it asks what has been the history of induced seismicity, one might refer to publications of Maurice Major, or Ruth Simon (1968,1969) indicating over 3000 instrumental quakes and 300-odd felt quakes in a couple of years northeast of Denver, where formerly there had been one felt quake (M = 6.7 ?, 1882) in all history. Refer to Guha, et. al, (1974) who have published a list of 25,000 quakes in several years of observations at Koyna, India, including the M = 7 event of December 10, 1967. That quake severely damaged the gravity dam, forming a horizontal crack below water-level at a change of section formed, as at Hartwell Dam, when the height was changed in mid-construction. In short, induced seismicity has been known to increase both the incidence (frequency) and intensity of quakes.

In the context of the summary of Piedmont reservoirs by Severy et. al. (1975), Clark Hill and Russell are among the class of "larger and deeper", have had more nearby quakes than the lesser reservoirs. Lake Anna, Virginia is the reference size, 305,00 acre-feet, 13,000 acres, maximum depth 21 m.

Item 2: To be sure, 25 psi stress changes are small compared to the 2-10,000 psi range of total stresses that must be acting in the hypocentral depth range of interest. Injection well quake stimulations at Denver, Rangely, and Attica, N.Y. were by changes on the order of 1,000 psi, but reservoir stimulations have been effected by changes computed to have been 92 psi at Kremasta, 44 psi at Kariba and 68 psi at Koyna, as examples of the thin margins of strength apparently acting. Such small threshold margins existing are consistant with computed stress-drops, on the order of 100 psi for many quakes. The observed dispersion of natural earthquakes, in time and place, suggests that on the great variety of faults in a given rock volume, there exists a range of threshold values, probably on the order of the maximum stress drop. Since reservoirs produce changes that are a fraction of the range, some reservoirs may happen to stimulate seismicity and others not, according to the state of stress of the underlying volume, which may typically be within 100 psi or so of failure.

Item 3: Because of its importance in computing horizontal stress changes upon changes of vertical stress (see Snow, 1972) that are calculable from geomorphic and hydrogeologic events, Poisson's ratio has been subject of research by the writer for about 5 years. In the course of field study of the Palo Verde Nuclear Plant Site Arizona (unpublished report to Fugro, Inc., July, 1974), it was found that $\nu = .38$ for basement rock in the Basin and Range, because otherwise, the deeply-alluviated portions of the province would be more active seismically than they are, compared to the youthful, active

western portion of the province. Analytical work conducted for the U.S. Geological Survey under Contract 14-32-0001-1255 utilized finite-element models of fractured masses in plane-strain, incorporating representative properties of normal and shear stiffness for fracture sets cutting rock at various dip angles, to compute lateral stress changes. The continuum-equivalent mass would have Poisson's ratios of 0.25 to 0.59 to account for the effects, such as wedging.

Item 4: A translation of "a degree of seismicity" might be "there is some seismicity". The wording was intentionally chosen to convey indefinite measures of frequency, magnitudes, etc, but to indicate certainty that failure is taking place. Ruling out source mechanisms other than fault slip with resulting elastic rebound, sliding-failure regions are stressed accordingly critical in magnitude and direction, specifically "on some pre-existing fractures", not all. No better evidence can be expected: insitu stress and strength measure would be poorer proof of criticallity.

Item 5: Response to Dr. McLean's paragraph 2, above, will not be repeated here. If the logic is fully understood and still remains unacceptable, then a search for a wholly new approach to induced seismicity should be initiated. Any constructive suggestions will be avidly devoured.

Item 6: The argument in lines 9-19 of page 7 of the report can be summarized, "upon examing the conflicting evidence, the writer prefers the assumption that high horizontal compression exists". Typical of earth-science data, a value-judgement has to be made of each source of data. The conflicting evidence of

normal and wrench-fault focal-plane mechanisms at Clark Hill has been questioned elsewhere, in reviewing Talwani's 1976 paper for the attorneys for the Corps (letter of December 13, 1976).

Item 7: Basement pore-pressure changes may conceivably range from zero (as in the case of the aquiclude separating the reservoir from the underlying pervious basement) to the full reservoir change (as in the case of dead-ended conduits, like wells or open faults in the reservoir). One-half the reservoir head is a defensible figure to approximate conditions that cannot be known without extensive field determinations. See Figure 2.

Item 8: Seemingly, author and critic are saying the same thing, and neither statement is worth much.

Item 9: The writer can see no rewording that would state the concept more clearly, but would value any suggestion that would tend to avoid being misconstrued.

Item 10: When an investigator has the sense to point out alternatives besides the conditions preferred because of assembled evidence, the valitity of the study is improved. Such is the effect of the passage cited, to which Dr. McLean finds objection. A fuller evaluation of one of the stress alternatives namely normal faulting, is included in response to Dr. Krinitzsky's comments.

The following refer to Dr. Ellis Krinitzsky's comments.

1. This paragraph is expository and requires no comment by the writer.

2. Paragraph 2 reflects a notion that dies hard among geologists, namely that it is the weight of a reservoir that

produces earthquakes. Carder (1948) demonstrated that Lake Mead produced a broad 18 cm subsidence depression. Carder (1945) noted the relationship of earthquakes to filling and cycling of Lake Mead. Few recognized the former to be a total-stress phenomenon, the latter an effective-stress phenomenon. Gough and Gough (1973) perpetrated the misconception with their computation of shear stress beneath Kariba Lake. Another reason for dubious reception of the effective-stress concept is that many still feel that basement rocks are impervious. Years ago, Secor (1965) showed that fractures owe their persistence with depth, to several km, to pore-pressure acting in them. Because water is known in mines at least 3.2 km deep, and for other reasons, geological and seismological, it is apparent that shallow earthquakes occur in water-saturated rock, even if porosity is minute. The pore-pressure change at several km below a reservoir is a function of the heterogeneity modifying the potential-distribution system. But, as explained on page 12 and Figure 2 of the report, an average condition, especially for rocks whose principle conductivity is in planes across the reservoir axis, is a symmetric flow system with half the reservoir potential (thus pressure) change expected at the bottom of the flow system.

As shown by Boussinesq, or more effectively by Newmark, stress on a finite surface area is rapidly attenuated with depth and distance away. The dead-weight of a reservoir has an effect that may readilly computed by superpositon of numerous point-loads representing elements of the water body, as did Gough and Gough. For an infinitely extensive reservoir

of uniform depth, the stress (vertical) equals the reservoir pressure. A reservoir spread throughout a watershed by its many tributary arms would have a similar averaged effect at depths of several km. In this exercise, the total reservoir volume was assumed spread over the watershed, and dead-weight loading was thus computed as 4 ft of water, i.e. 2 psi compression. Clearly, it is more beneath the deep end of the reservoir, and less under divides. Earthquakes may take place where there is the greatest decrease of effective stress, as well demonstrated by the distribution of epicenters around Hsinfengkiang Reservoir China (Chung-kang, 1974). Shaped like a bottle, the reservoir has two narrow canyon reaches separated by a large flooded valley. Because the dead-weight compression is small under the canyon reaches, quakes have been concentrated there, whereas the weight of the large water body cancelled the pore-pressure effect under it.

3. This seems a valid statement, depending upon topography.

4. In this paragraph are statements suggesting some chronological confusion. The magnetic stratigraphy of the Atlantic sea-floor volcanics do show at least hundreds of miles of continental drifting since mid-Cretaceous. There has been recorded only compression tectonics (thrusting) since that time. To be sure, changes in horizontal stress may well have taken place during drifting. There could have been periods of sub-critical stress by processes related to the drifting, changes of base shear or resistance elsewhere. When a tendency for increased stress arose, it had to produce failure and thus remained limited by the strength of the faulted crust. The

relaxations recorded by the Triassic grabens preceeded the post-Cretaceous period of interest. There is a good stratigraphic record of Tertiary evolution, and it appears to have been continuously like the early-Tertiary, when there was compressional faulting.

Dr. Krinitzsky repeats the belief that one should start with assumptions about the current state of stress, and then analyze the effect of the reservoir. This has already been done (as illustrated by pre- and post-reservoir stress states in Figure 4). This is a less powerful analysis than one which also examines the late historic changes for evidence of continued criticallity, or development of a threshold of safety. A well-thought-out program of insitu stress measurement will eventually be warranted for some reservoirs, but the cost will be two to three orders of magnitude beyond the present study.

5. The reviewer states that Dr. Snow places a hinge line at the boundary of the Coastal Plain. Quite the contrary, no such hinge nor assumed position was used. The unconformities shown beneath the Coastal Plain are in their present positions, based on well data, and their prolongations are shown dashed over the Piedmont. The basement must have tilted as a unit, not bent at the Fall Line, for the volumes of cut and fill, averaged over the Atlantic seaboard, must be nearly balanced. Contrary to the casual theory that hinge lines move outward towards the continent as a basin subsides, it is apparent that the shore-line, a better demarcation than a "hinge", moved first landward from Cretaceous to Eocene time, since the continental Tuscaloosa beds were onlapped by estuarine and neritic Eocene beds, as shown.

Note that the intersection of the base of the Tuscaloosa (prolonged) with the base of the Ellenton lies 25 miles landward of the Fall Line. The base of the Congaree intersects the Ellenton 10 miles further east; the base of the McBean intersects the Congaree nearly 10 miles east of the Fall Line. Clearly, the shoreline has progressively shifted seaward, even to the close of the Pliestocene. No matter, the important thing in this project is the correct representation of uplift, for which Figure 5 suffices if modest precison is all that is needed for qualitative correctness.

6. Reasons for preferring a thrust-fault model for the Russell area have been enumerated already, in the report and rebuttal. The objection raised in paragraph, 6, that Clark Hill microearthquakes indicate normal faulting, is, of course debatable. Talwani's interpretations are inconsistent and tentative. It is illigitimate to subdivide arbitrarily a scatter-diagram of compressional and tensional axis from a small *number of events into two* different mechanisms. The writer's feeling on that interpretation has been borne out by Dr. Maurice Major, but the seismologists on the Board may have other views, better founded. There are Tertiary thrust faults, anticlinal folds and compressional insitu tests and focal-plane mechanisms as evidence for high horizontal stresses. There are noknown normal faults nor other evidence of extension. The Blue Ridge Front is a very debatable normal fault-line scarp.

7. No comment is made on this correct statement.

8. Paragraph 8 is in agreement with the report. All earthquakes not related to volcanism are probably due to

regional tectonism, including reservoir-triggered events and swarms. The McCormick swarm may have been independent of the reservoir, or just as well, its occurrence, otherwise inevitable, may have been stimulated by increased pore pressure to take place sooner, or closer to the reservoir. Similar arguments may pertain to the August 1, 1975 quake near Oroville Reservoir in California. Its normal fault is propagating now, towards the reservoir, but its inception, 8 years after filling, may also have been modified by the regional piezometric effects. A "hot spot" is a notion consistent with the idea of a rock mass stressed to the limit of strength of major bounding planer structures. Within such boundaries, there will be a nonuniform stress field whose small stress range is dictated by fault orientation, continuity, filling materials, roughness, as well as the history of failure releases with such detailed pore-pressure effects as result from varied dilatations and hydrodynamic recovery processes.

9. Paragraph 9 is a true comment.

10. The analogy of the crust to a glacier has its merits, as well as some objectionable features. A more plastic asthenosphere is distinct from the brittle, shallow crust where quakes of interest have their focus. But to have horizontal tension coexisting with compression is hard to envision. There is no relative motion of the Southern Appalacian crust with respect to other nearby plate elements. In the absence of major fault movement since Miocene, at the latest, it looks as though the Piedmont moves as a body. Glacial cravasses form by flexure at ice-falls and by drag against walls. Further,

gravity drives glaciers, whereas continents are driven by mantle convection, and compression is transmitted through the crust far from the site of base shear.

11. There is room for healthy speculation, such as paragraphs 10 and 11 contain, to explain the observed "hot spots". Neither explanation, of Krinitzsky or Snow, is going to be resolved right away.

12. One consequence common to both models is mentioned here. Krinitzsky sees the maximum quake limited by the dispersal of motion along a zone of relative movement. In Snow's model, quake magnitude may be limited by the stress threshold attainable hydraulically. In both, the scale of heterogeneities may govern magnitudes: if the rock is minutely segmented by faults, perhaps according to its age or its prior experience, a critically-stressed volume may not attain sufficiant size, fault area or volume for large energy release.

13. An noted, such nuances are beyond present capabilities; all that the writer *has ever claimed is a* criterion of failure vs. non-failure. It says nothing about the severity.

Though it is not obvious, the mechanism of stress decrease by reservoir filling works also for normal faulting. Recognizing the weak possibility of normal faulting, it was promised on page 25 of the report, that the normal-fault alternative would be analyzed. Failing to include it in the report, it is here appended.

In normal faulting, σ_1 is vertical, σ_3 horizontal. Since vertical stresses change more than do horizontal, a stress circle shrinks as it shifts to the left. Whether or not it moves closer or farther from the envelope depends upon the slope, ϕ.

If

$$\frac{\Delta\sigma_3}{\Delta\sigma_1} > \frac{1-\sin\phi}{1+\sin\phi} ,$$

it moves towards failure upon decreased stress. With $\phi = 30°$, and the circle tangent, $\Delta\sigma_3 / \Delta\sigma_1 > 1/3$ is the failure criterion. As table I shows, from mid-Cretaeous (step 1) to end-Miocene (step 4), $\Delta\sigma_3/\Delta\sigma_1 = .665$, so continued normal faulting would have occurred (there is no evidence for it).

There is a suggestion, from clastic dikes in the Coastal Plains, that there was Mio-Pliocene (?) seismicity. From that time to the present $\Delta\sigma_1 = -8.$, $\Delta\sigma_3 = +10.$, so the criterion fails, meaning, there is not good reason to expect normal faulting today <u>if</u> stress had been released by failure in the Piocene.

The filling of the reservoir, over rock currently failing by normal faulting, as favored by Dr. Krinitzsky, gives $\Delta\sigma_1 = -25.$, $\Delta\sigma_3 = -26.$, so failure would be induced, not inhibited.

14. In this pregnant paragraph, Dr. Krinitzsky objects to the wording, "There is scant evidence (except Koyna) that the maximum probable quake may exceed the expectation of natural events.....", claiming that on the basis of Dr. Snow's report, there is <u>no</u> evidence, rather than "scant".

The analysis of data from the site in question, the Piedmont and adjacent provinces, yields no evidence, that is true, but the Koyna experience is still valid and pertinent. Lacking theory and data to contridict the possibilty that an unusual quake, like the Charleston event of 1886, could be induced by a new reservoir, such as R.B. Russell, there must be allowance made for seismic events beyond the realm of events anticipated

only from pre-reservoir statistics.

It is the writer's belief that the chances of an unusual induced event are small. We live with, and design within such hazards. A flood that would overtop the R.B. Russell embankments, for instance, is accepted as a possibility, reasonably well evaluated by a body of hydrologic statistics. For an unusual induced seismic event, we have poor statistics. Only one known reservoir among many hundreds in the world has done that, and four on the Savannah have had little seismic response. But that small hazard must be recognized by all concerned, evaluated and placed in proper prospective. It cannot be swept under the rug.

The writer subscribed to adoption of a magnitude 5.5 quake at the damsite because it was a very positive, conservation design precedent. It is the first time that a major U.S. design agency has translated to the damsite the maximum regional quake that would have occurred elsewhere but for the possibility of reservoir-induced seismicity of doubtful character. Because of the conservatism so built into the design earthquake, the writer feels that prudence does not demand adoption of a nearby quake in access of M = 5.5.

15. Dr. Krinitzsky concludes, in concert with his colleagues, that the report is technically deficient. It is obvious that the deficiency is that it reaches two conclusions unpalatable to the Corps of Engineers: 1) Richard B. Russell Reservoir embodies circumstances that could generate induced earthquakes, and 2) that there is a possibility, however small, that the maximum quake generated may exceed the maximum natural events. The writer was commissioned to use the most advanced art to review

and speculate upon the processes affecting induced seismicity in that portion of the Piedmont. The report was written with the aid of the most advanced techniques, since the writer is the principle originator of the art; indeed the art was improved in the process of work in the Russell project.

It is pointed out that the original verbal contract assured the writer of the services of a Savannah District geologist, who would work out the field relationships needed for the analysis, especially the geomorphic evolution. With the help assured, agreement was reached for $3000 compensation for all aspects of the report. It developed that the geologist, William Hancock, was assigned other duties, so could not do the writer's bidding, nor could Dr. Lutton, who was so requested. Upon lodgement of a complaint, the writer was told by Dr. Krinitzsky to "make some simplifying assumptions and proceed with the analysis". Unwilling to compromise on quality of workmanship, the writer worked essentially full-time from September through December. The field and literature work utilized all available time until November 18, 1976, and afforded only a month for analysis and report preparation. It is estimated that $13,000 worth of time, materials and hired help went into the report, without substantial remuneration except the $3000, plus about $1000 conveyed as preparation for board meetings.

The report is not deficient from neglect nor applied expertise. Its technical soundness will stand up to scrutiny of unbiased peers.

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Appendix 1
Section G
end.

GEOLOGICAL AND SEISMOLOGICAL
EVALUATION OF EARTHQUAKE HAZARDS
AT
THE RICHARD B RUSSELL PROJECT

APPENDIX 2

APPENDIX 2
SELECTED EARTHQUAKE RECORDS

PIEDMONT EARTHQUAKE

Reverse Fault

1. San Fernando Earthquake, 2/9/71, Griffith Park Obs., CIT File No. 0198, S 00 W.
2. San Fernando Earthquake, 2/9/71, Pacoima Dam, CIT File No. C041, S 16 E.
3. San Fernando Earthquake, 2/9/71, 445 Figueroa Street, L.A., CIT File No. C054, N 52 W.
4. San Fernando Earthquake, 2/9/71, Hollywood Storage P.E. Lot, L.A., CIT File No. D058, N 90 E.
5. San Fernando Earthquake, 2/9/71, Castaic Station, CIT File No. D056, N 21 E and N 69 W.

Strike Slip

6. Parkfield Earthquake, 6/27/66, Cholame Shandon Array No. 2, CIT File No. B033, N 65 E.
7. Parkfield Earthquake, 6/27/66, Temblor Station S 25 W, CIT File No. B037, S 25 W.

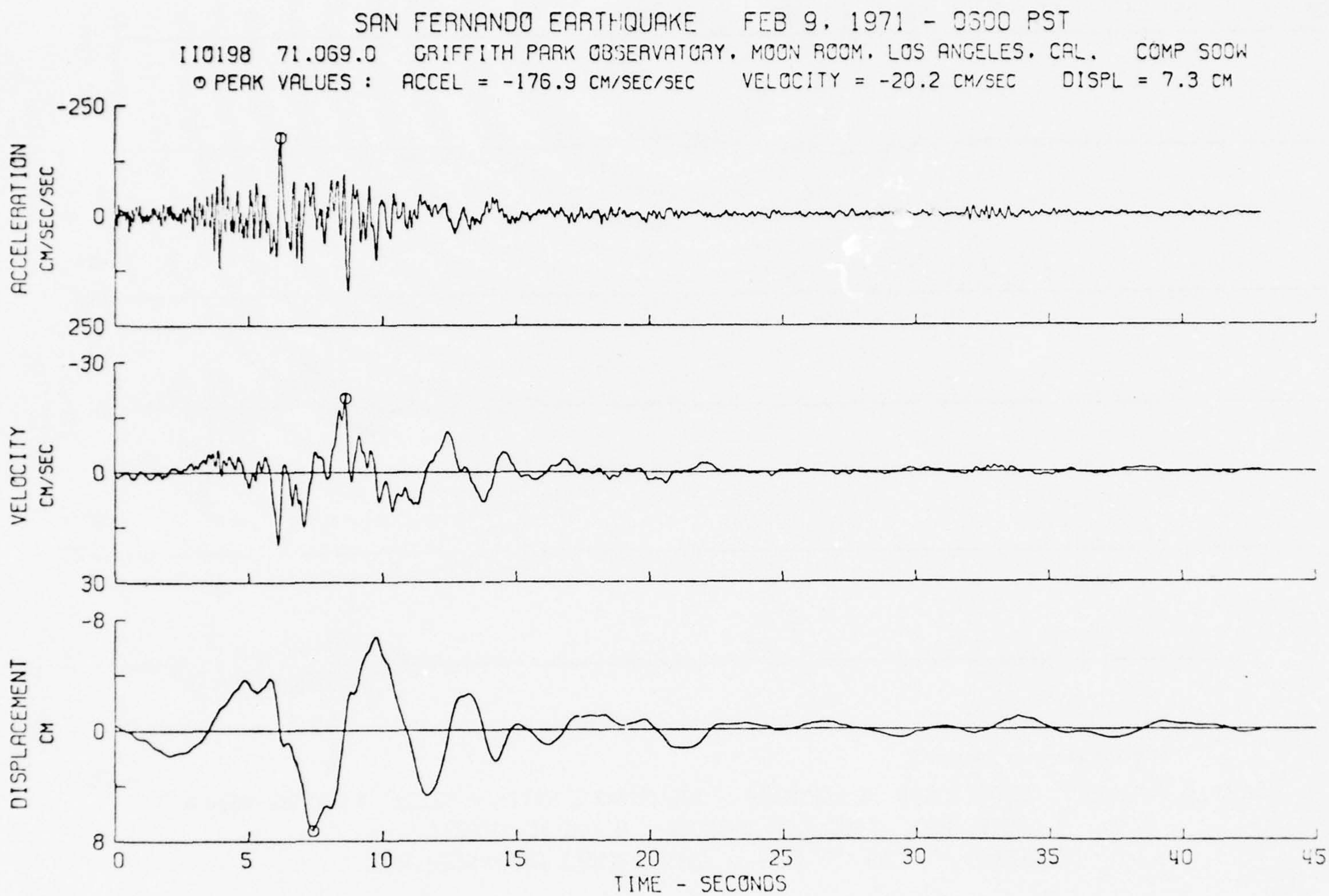
Normal Fault

8. Helena, Montana, Earthquake, 10/31/35, CIT File No. B025, N 90 E.
9. Oroville, California, Earthquake, 8/1/75, Component N 37 E or N 53 W, Peak Acc. = 0.10 - 0.11 g.

10-11. Koyna Earthquake, India, M = 6.5
Longitudinal: a_{max} = .63 g; v_{max} = 32 cm/sec; d_{max} = 13.3 cm
Transverse: a_{max} = .49 g; v_{max} = 20.08 cm/sec; d_{max} = 31.64 cm

CHARLESTON AND NEW MADRID EARTHQUAKES

12. San Fernando Earthquake, 2/9/71, 1625 Olympic Blvd, Los Angeles, CIT File No. 0199, N 62 W
13. San Fernando Earthquake, 2/9/71, 3411 Wilshire Blvd, Los Angeles, CIT File No. S265, W



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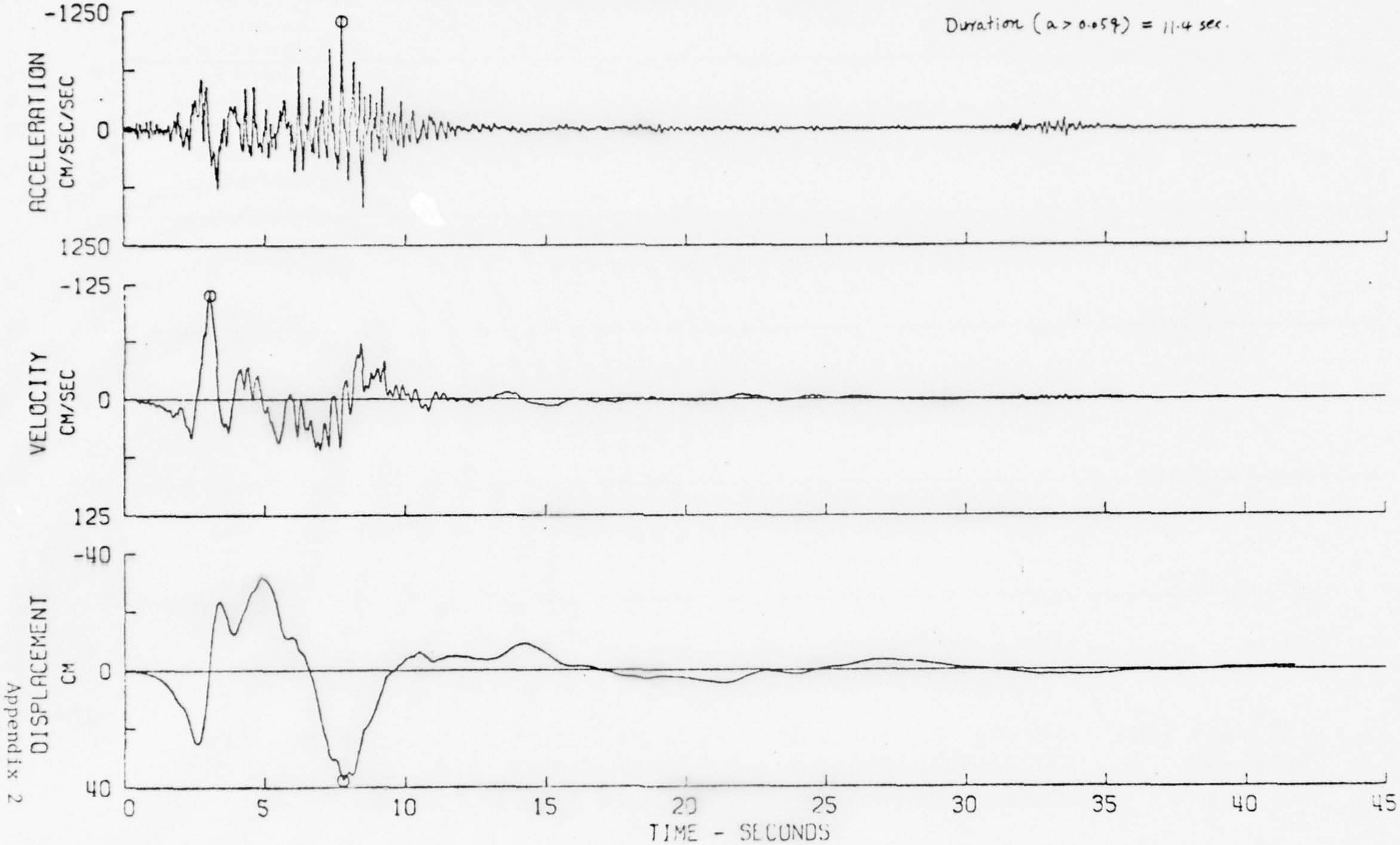
Section A

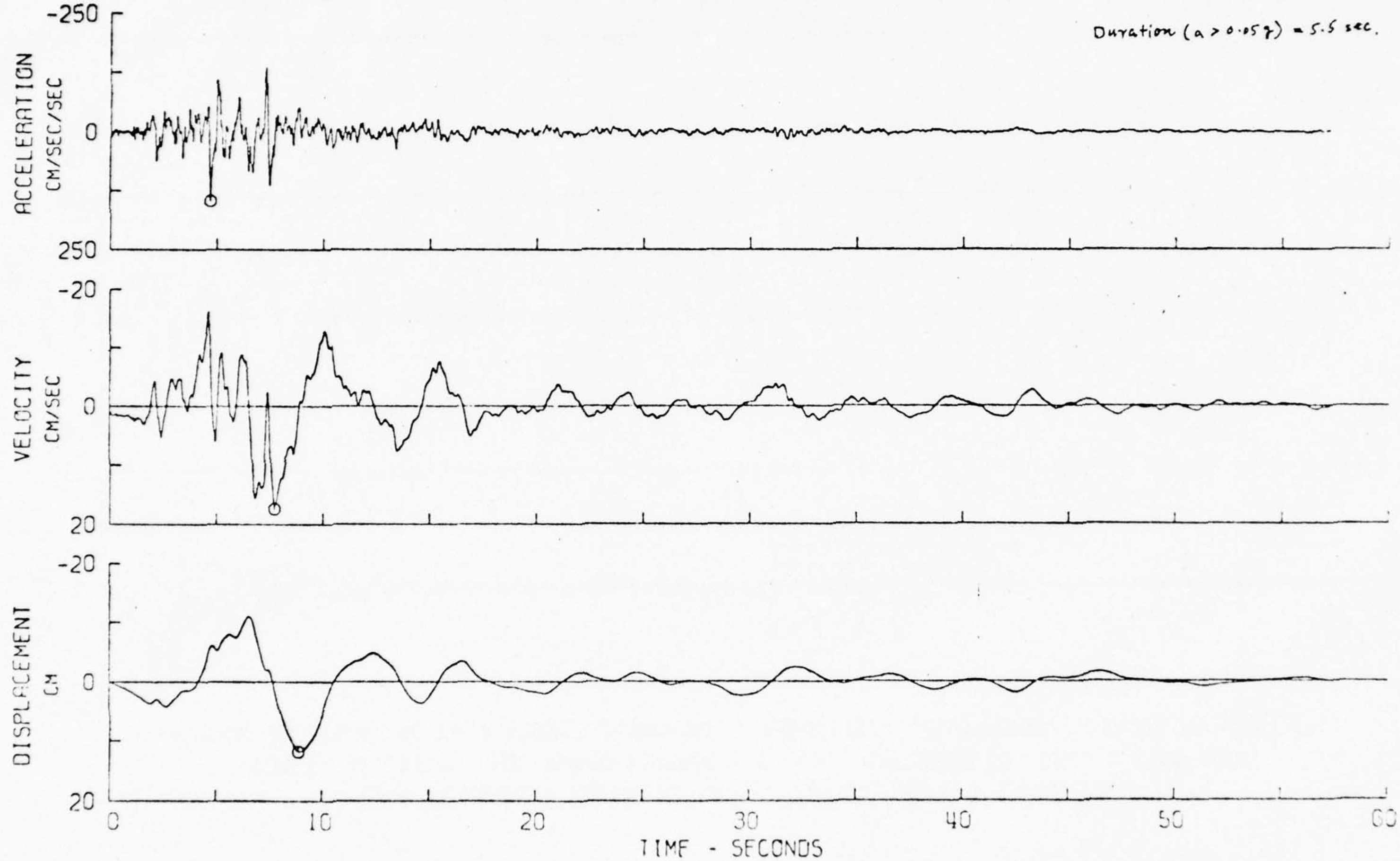
SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST
IIC041 71.001.0 PACOIMA DAM, CAL. COMP S16E
⊙ PEAK VALUES : ACCEL = -1148.1 CM/SEC/SEC VELOCITY = -113.2 CM/SEC DISPL = 37.7 CM



SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST

IIC054 71.060.0 445 FIGUEROA STREET, SUB-BASEMENT, LOS ANGELES, CAL. COMP N52W

⊙ PEAK VALUES : ACCEL = 147.1 CM/SEC/SEC VELOCITY = 17.4 CM/SEC DISPL = 11.8 CM

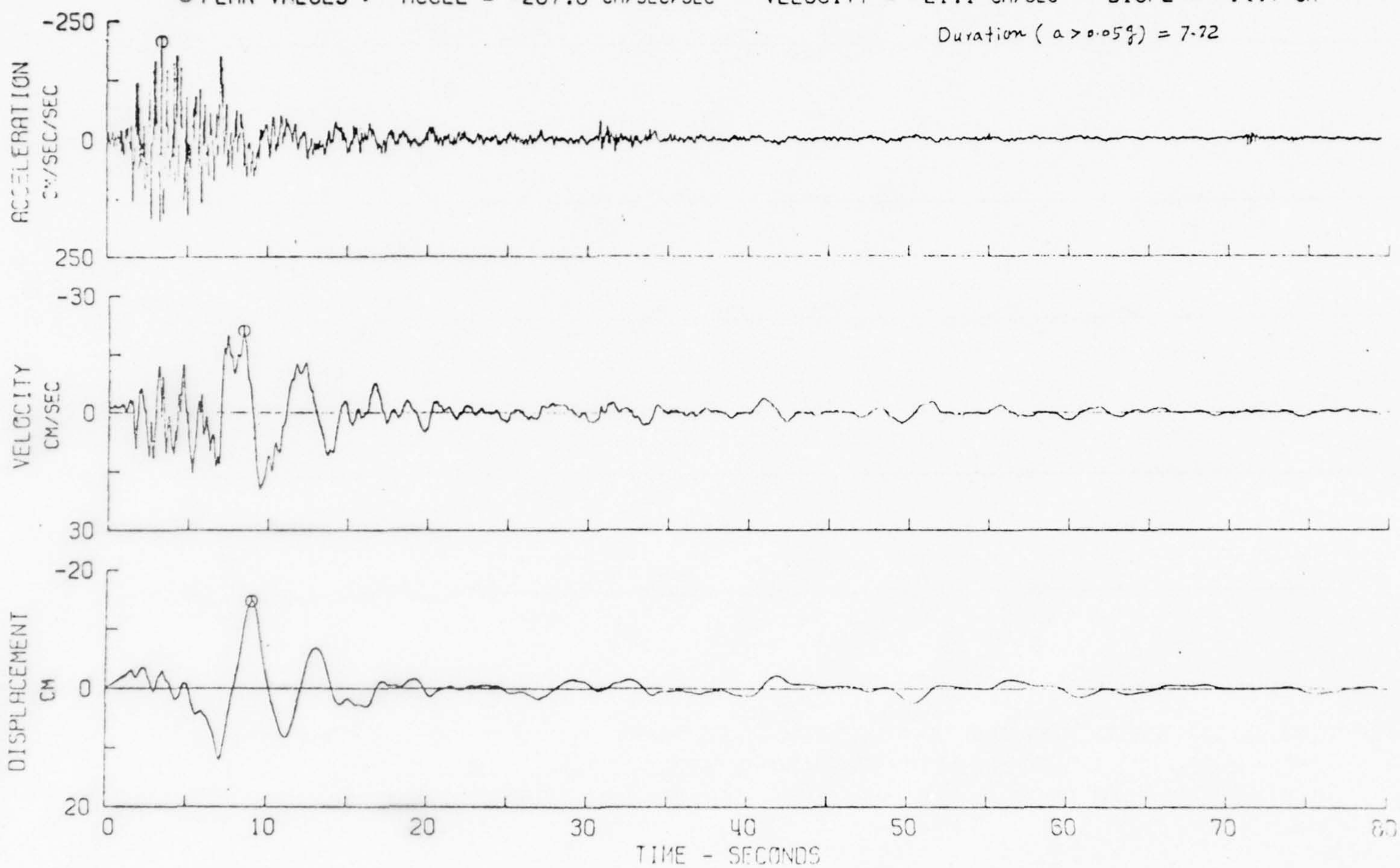


SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST

IID058 71.155.0 HOLLYWOOD STORAGE P.E. LOT, LOS ANGELES, CAL., COMP N90E

⊙ PEAK VALUES : ACCEL = -207.0 CM/SEC/SEC VELOCITY = -21.1 CM/SEC DISPL = -14.7 CM

Duration (a > 0.05g) = 7.72



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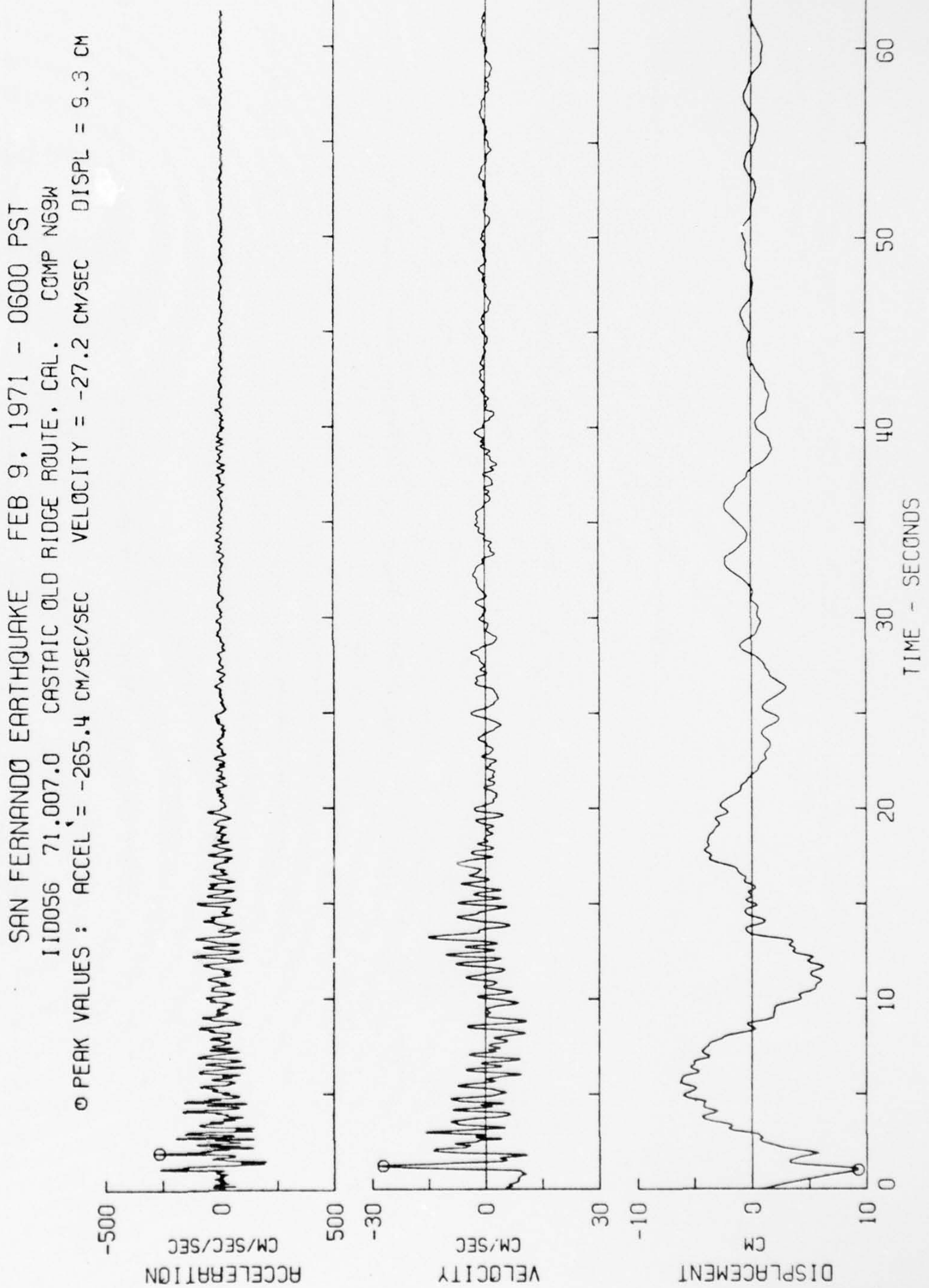
Section A



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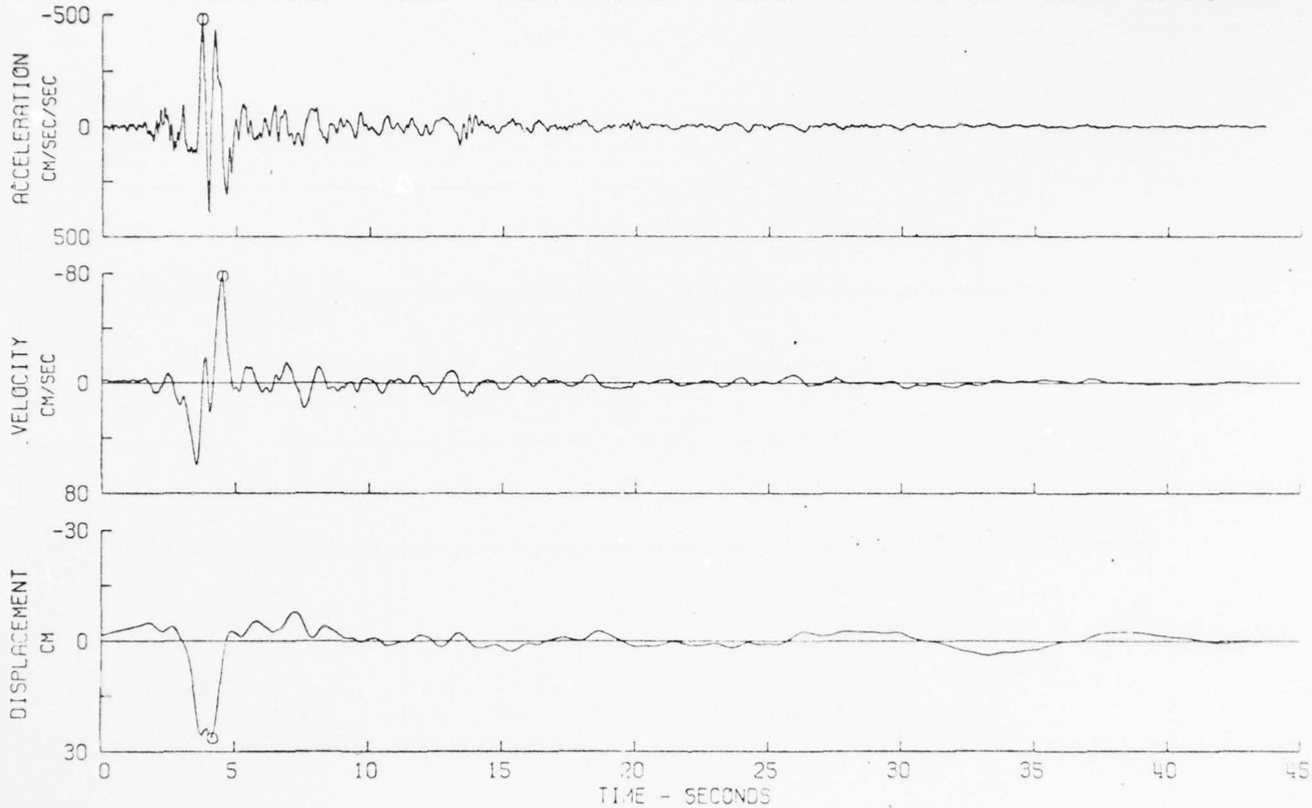
Section A

PARKFIELD, CALIFORNIA EARTHQUAKE   JUNE 27, 1966 - 2026 PST

IIB033 66.001.0   CHOLAME,SHANDON, CALIFORNIA ARRAY NO. 2   COMP N65E

⊖ PEAK VALUES : ACCEL = -479.6 CM/SEC/SEC   VELOCITY = -77.9 CM/SEC   DISPL = 26.3 CM



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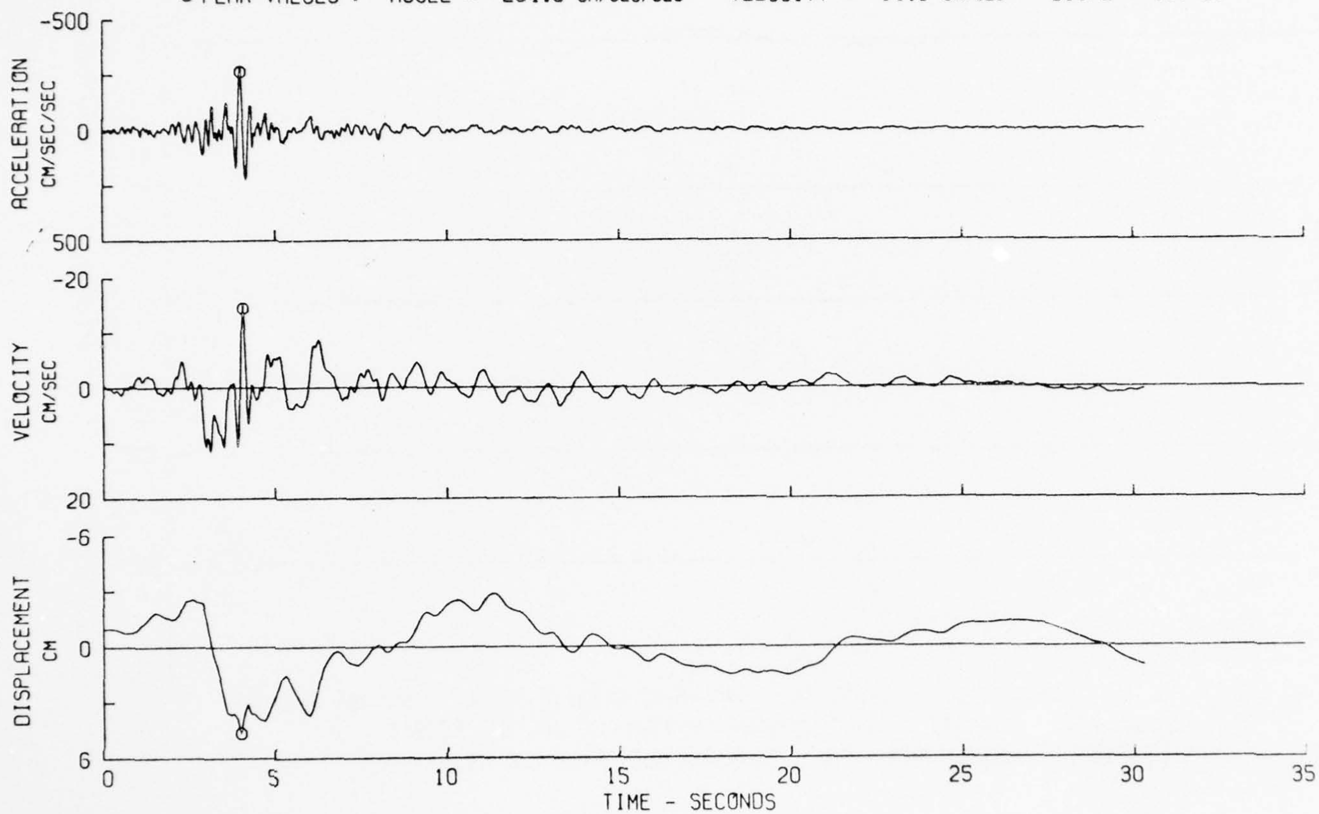
Section A

PARKFIELD, CALIFORNIA EARTHQUAKE JUNE 27, 1966 - 2026 PST

IIB037 66.005.0 TEMBLOR, CALIFORNIA NO. 2 COMP N65W

⊙ PEAK VALUES : ACCEL = -264.3 CM/SEC/SEC VELOCITY = -14.5 CM/SEC DISPL = 4.7 CM



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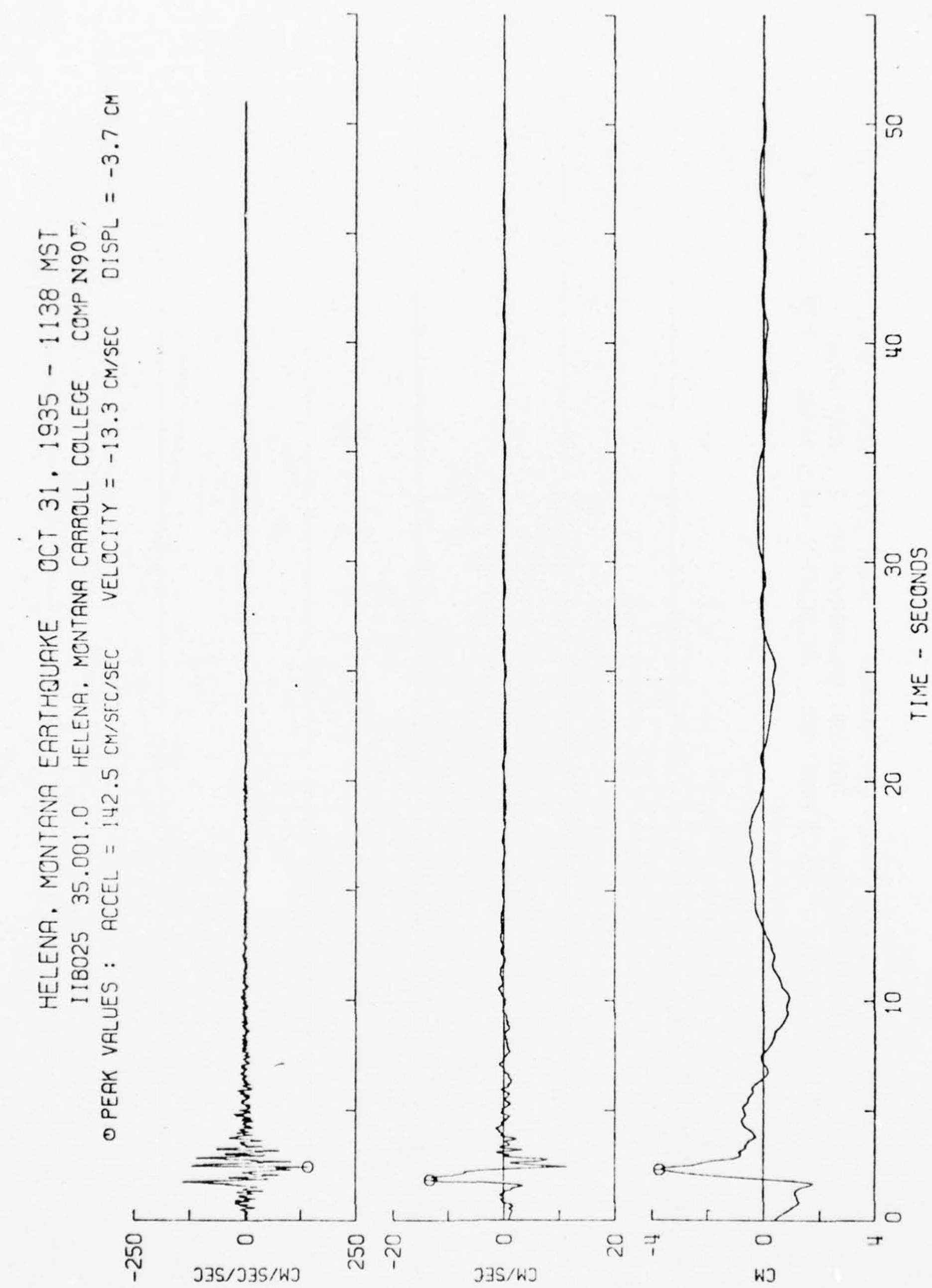
Section A



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Section A

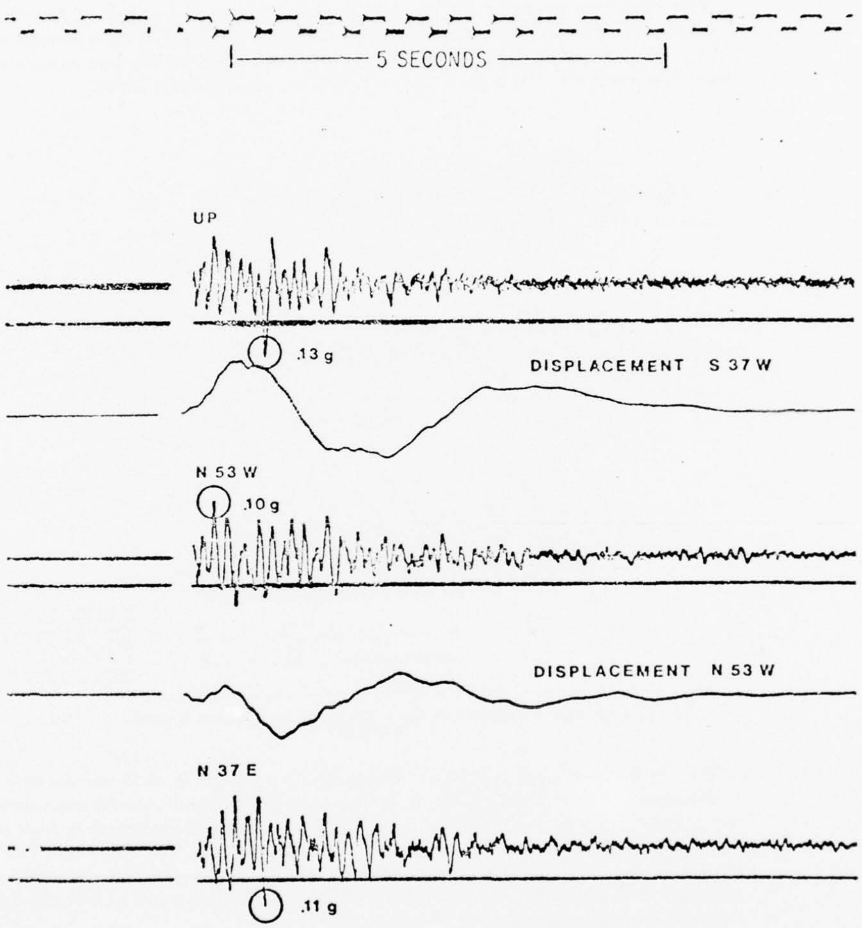

Figure 4. Tracing of the accelerograph record from the Oroville seismograph station about 2 km northwest of the dam. Normal fault

rected acceleration time data of the three components of this record are given in Appendix 'A'.

Ground Motion

The integrated ground velocities and displacements corresponding to the three components of motion are shown respectively in Figures 2, 3 and 4. A three dimensional plot of ground displacement is given in Figure 5. The integration has been carried out using Simpson's rule with a time increment of 0.01 second (Brady, 1966).

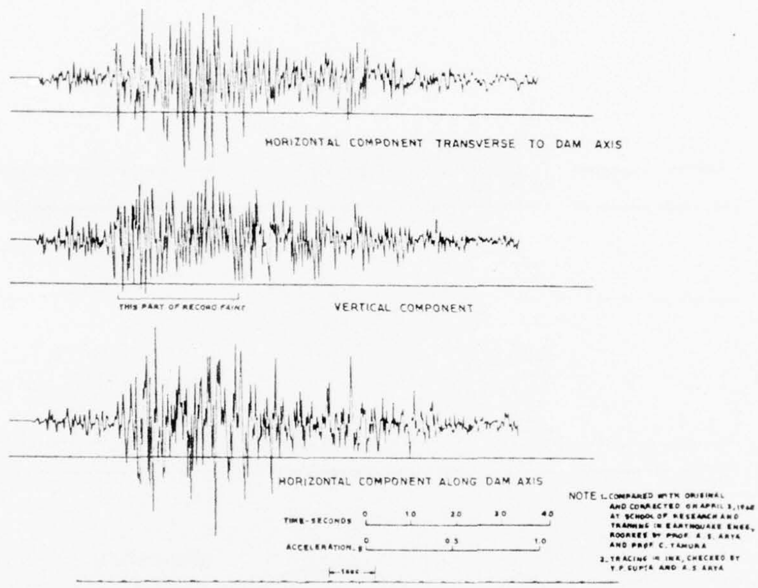

Fig. 1. Accelerogram Recorded at Block 1-A of Koyna Dam on December 11, 1967 at 04-21 *I.S.T.*

9.5236 cm/sec

The maximum ground velocity in longitudinal component is 24.19 cm/sec and a nearly equal value of 10.01 cm/sec 25.58 cm/sec in vertical component. The transverse component has a lesser value of 7.50 cm/sec 20.08 cm/sec. The maximum ground displacement is least in longitudinal component and maximum in vertical component. The values are 13.30 cm, 21.64 cm and 28.84 cm corresponding to longitudinal, transverse and vertical components. The peak displacements are obtained in the first wave and in the duration of record considered there are hardly two waves.

The three dimensional plot, Figure 5, gives a general idea of how a single particle has moved during the shock.

Response Spectra

Spectral values of displacement and velocity have been determined by assuming the ground acceleration to be composed of short duration trapezoidal pulses and using

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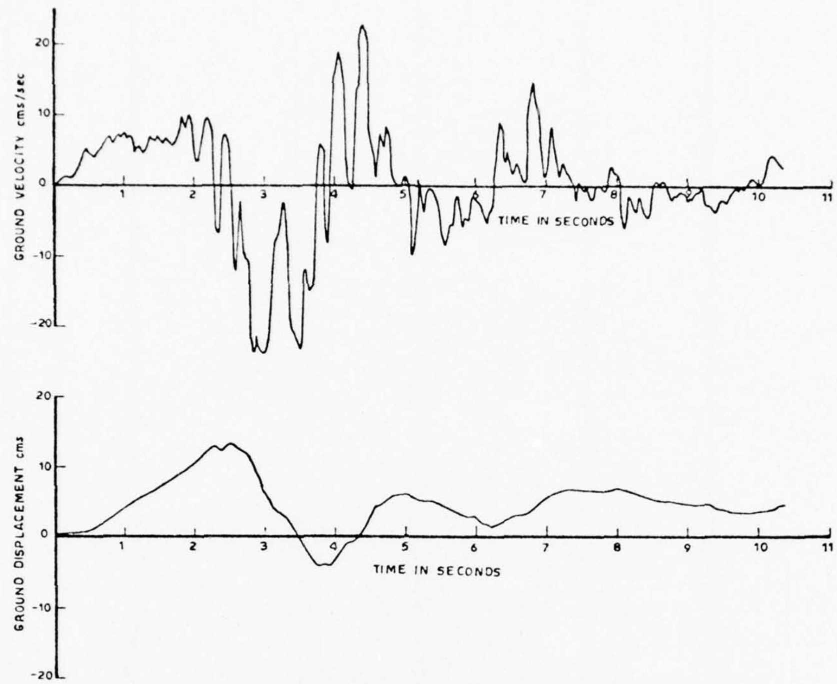


Fig. 2. Ground Displacement and Ground Velocity for Longitudinal Component.

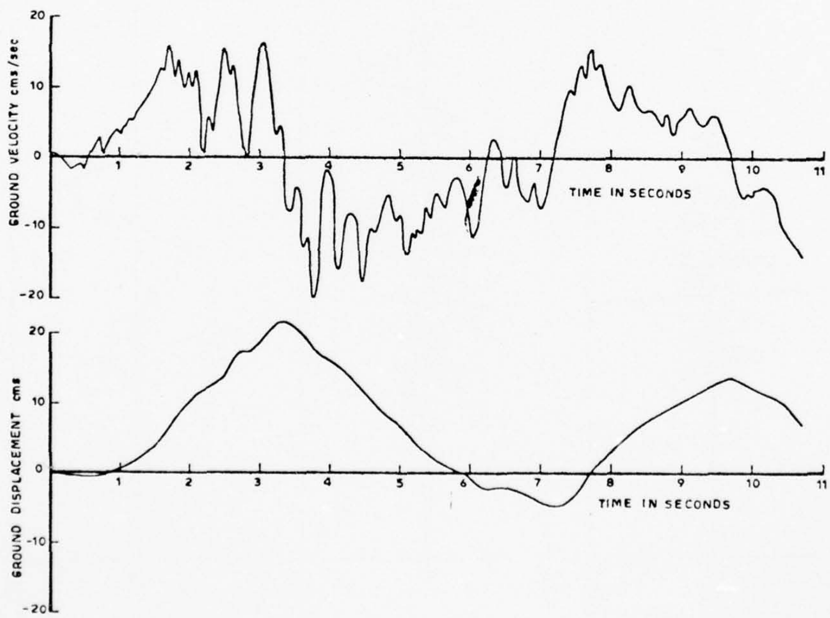
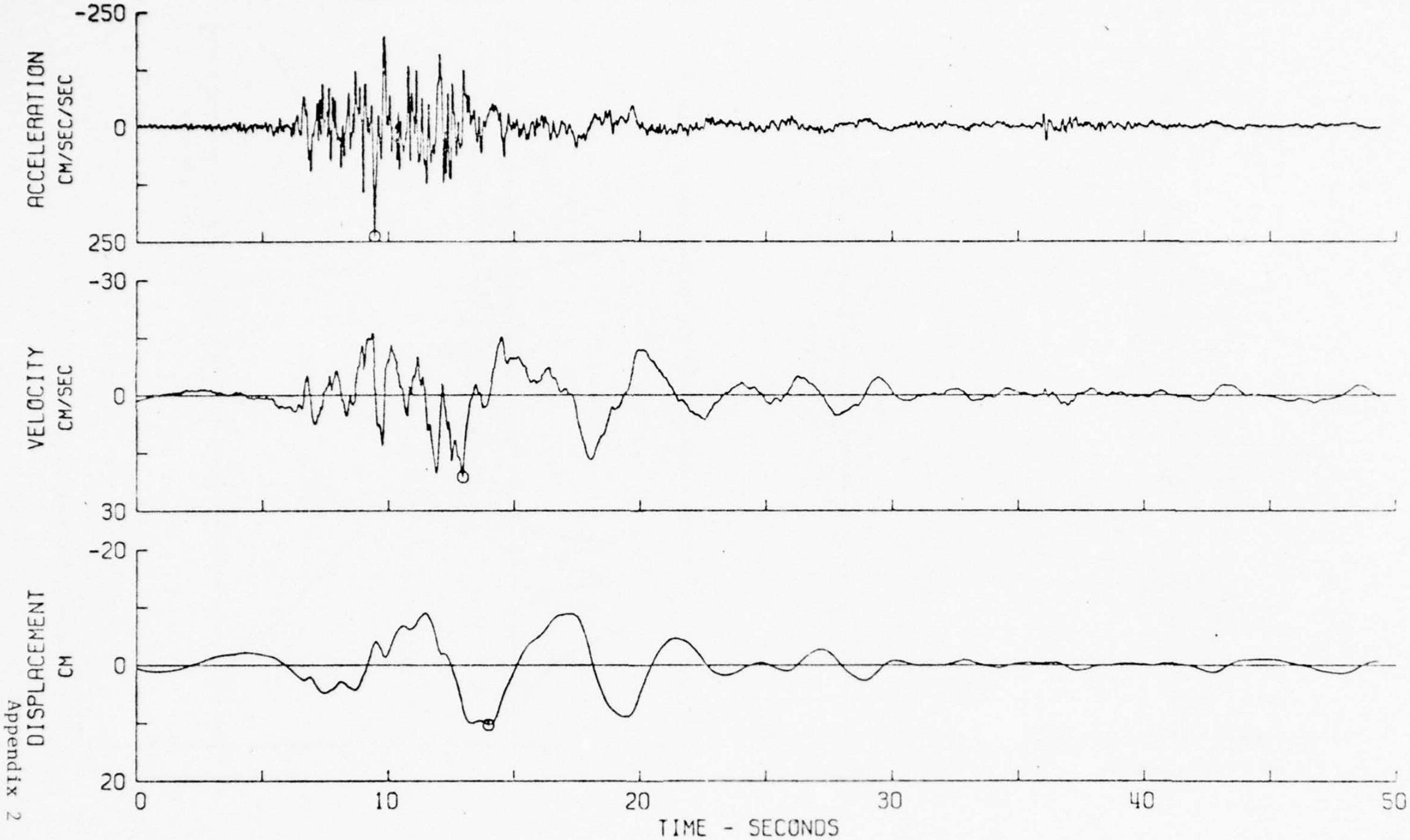


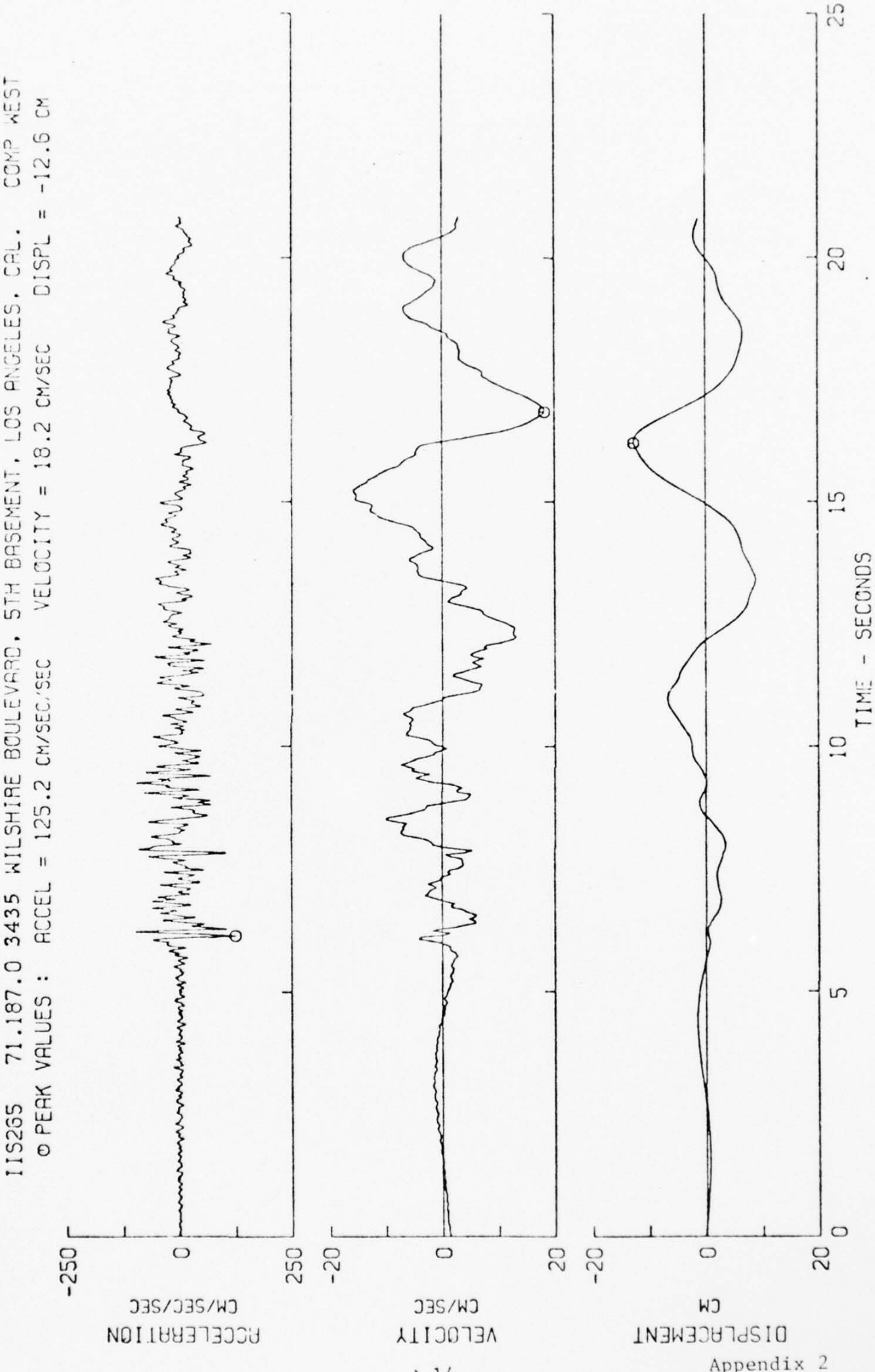
Fig. 3. Ground Displacement and Ground Velocity for Transverse Component.

SAN FERNANDO EARTHQUAKE FEB 9, 1971 - 0600 PST

II0199 71.072.0 1625 OLYMPIC BLVD., GROUND FLOOR, LOS ANGELES, CAL. COMP N62W

⊙ PEAK VALUES : ACCEL = 238.8 CM/SEC/SEC VELOCITY = 21.3 CM/SEC DISPL = 10.3 CM





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Section A

GEOLOGICAL AND SEISMOLOGICAL
EVALUATION OF EARTHQUAKE HAZARDS

AT

THE RICHARD B. RUSSELL PROJECT

APPENDIX 3

FIELD STUDIES OF SPECIFIC FAULTS AND OTHER STUDIES

SECTION A

Geologic Report on The Modoc Fault Zone,
South Carolina and Georgia.

10 November 1976

GEOLOGIC REPORT ON THE MODOC FAULT ZONE, SOUTH CAROLINA AND GEORGIA

1. SUBJECT: Field Studies Along the Modoc Fault Zone of South Carolina and Georgia

2. DATE OF STUDY: 5-16 August 1976

3. PURPOSE OF INVESTIGATION: (1) Field evaluation study of the tectonic history of Zone (2) Examination of local elements in the structural geology and faulting, and (3) Assessment of the evidence for active faults/faulting.

4. PERSON MAKING FIELD STUDY:

William E. Hancock, Geologist, SASEN-FG

5. PERSONS CONTACTED IN REGARD TO OUTSIDE INFORMATION:

Timothy Long, GA Technical Institute, 18 September 1976
David Howell, State Development Board, 12 September 1976
William Perkle, Akin Campus, University of South Carolina, 13 September 1976

6. OBSERVATIONS:

a. Detail mapping and transect was utilized in studying, examining and assessing the Zone. Figure 1 locates areas where detail and transect observations were made. The study was conducted during the continuous period of 5-12 August 1976. Further work was accomplished during September and October 1976. Outcrop and road lines were walked, and shoreline exposure was examined from the lakeside by boat. Contacts shown on detail maps were placed by walking the ground.

b. Contacts are extended to sections examined by transect study by projection. Location of contacts in transect studies are from outcrops and roadcuts, or by interpolation between outcrops.

c. The results of detailed reconnaissance and mapping are shown in Figure 2.

d. As shown on the map, rocks of the Modoc Zone can be grouped into Low and High Rank metamorphic grades. These correspond to the Slate Belt rocks of South Carolina, the Charlotte Belt, Kiokee Belt rocks of Georgia and South Carolina respectively. Intruded into these groups are younger multi-espisodic granite intrusions commonly adamellite in composition.

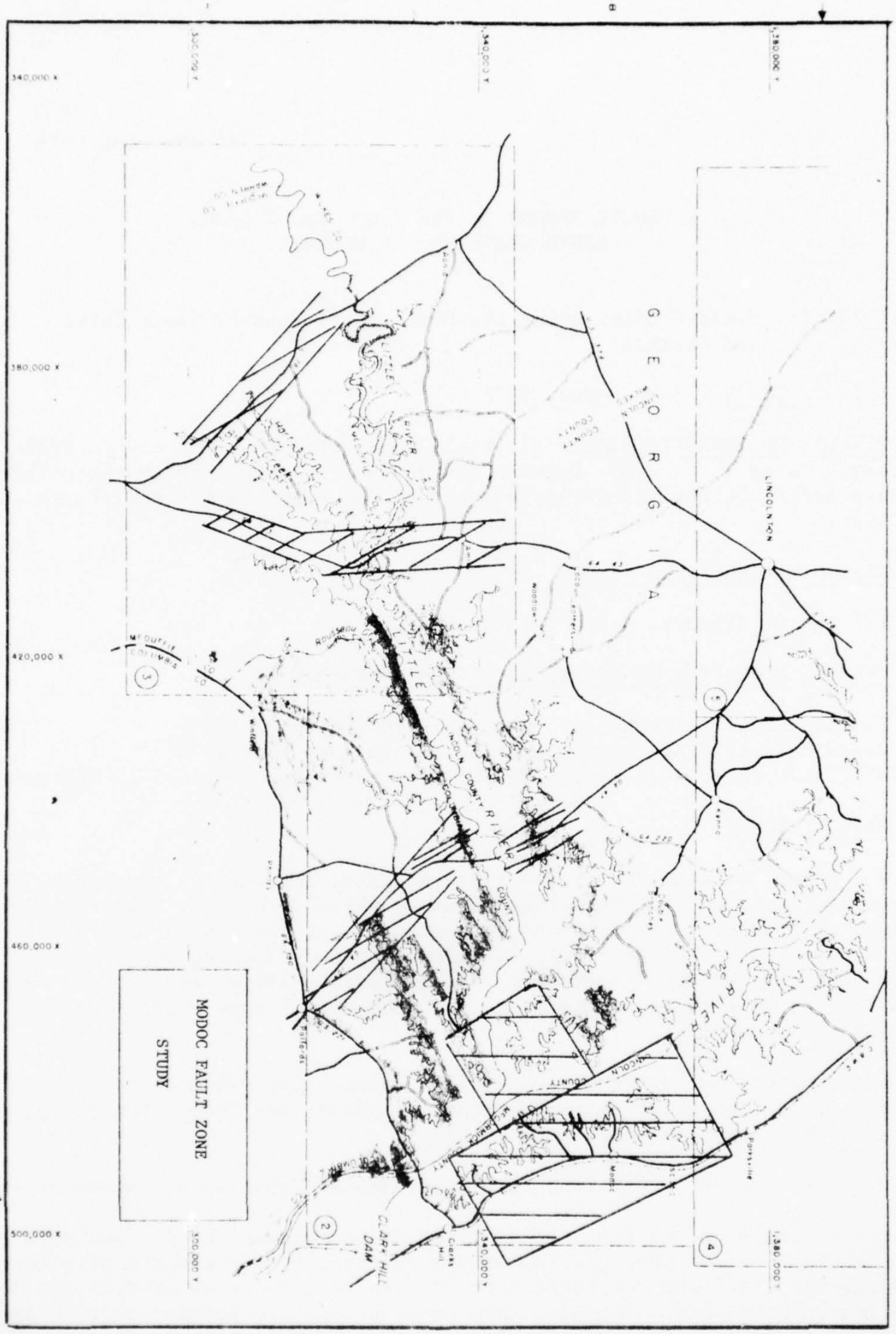
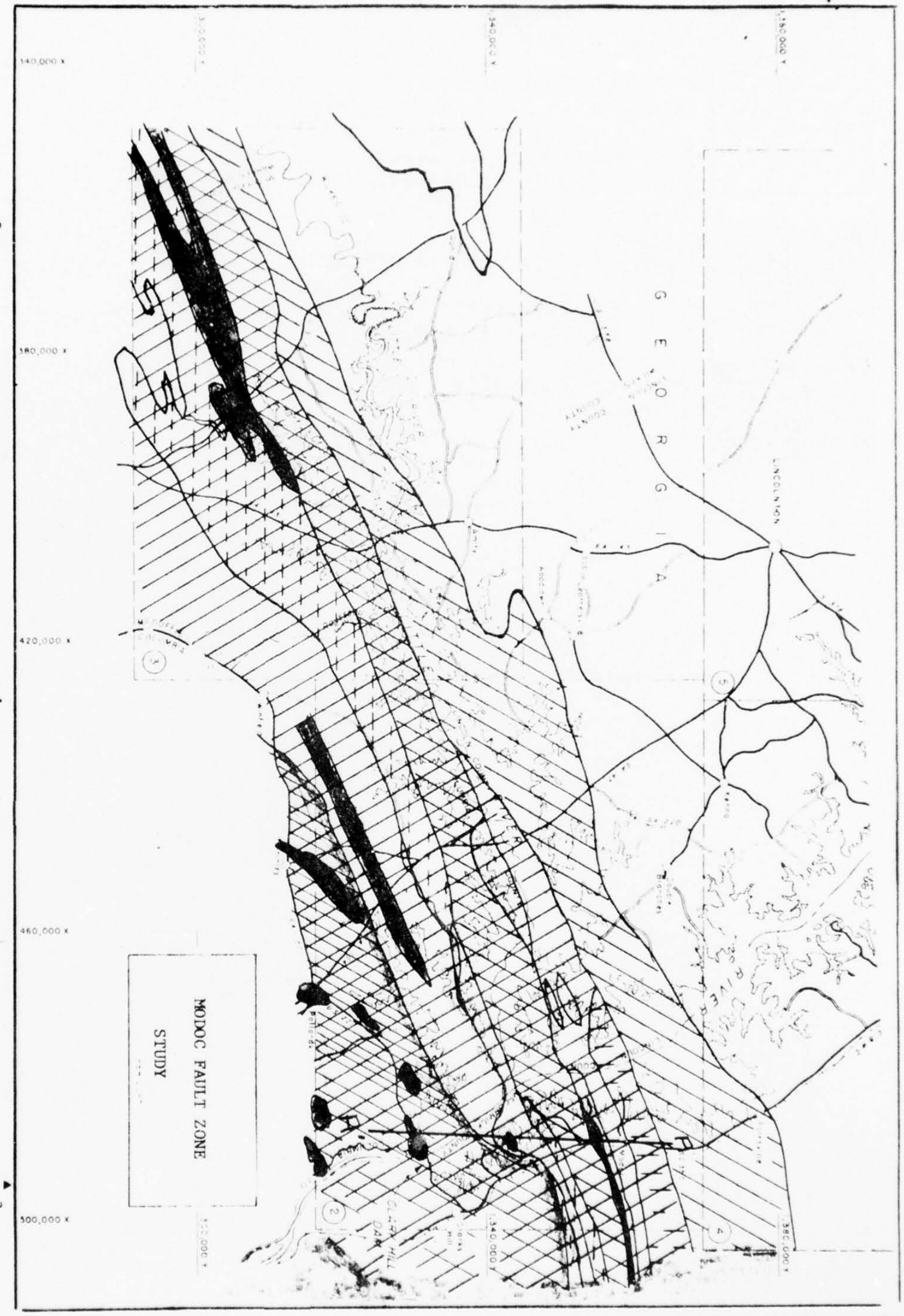


FIGURE 1   Location map of the detail and transect study performed on the Modoc Fault. Inclosed figures are areas of detail mapping, 1/12000 scale. Open figures and shaded areas are sites of reconnaissance mapping and study.



LOW GRADE ROCKS

Sericite mica schist

"Button"or"Knotty" mica schist

Mica schist and amphibolite

Sericite and muscovite schist and gneiss, mixed with some mafic chlorite schist, generally cataclastic to blastomylonitic

FIGURE 2

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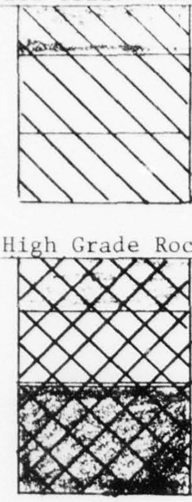
Section A

Low Grade Rocks



granitic gneiss, cataclastic

meta-argillite and sericitic phyllite, slaty.

Little River Series mafic volcanics, phyllites and argillites.

High Grade Rocks

Kiokee Biotite granit gneiss

mafic and untramafic rocks, including talc and chloritic schists

Granite, adamellite, undifferentiated as to episode

AD-A043 849 ARMY ENGINEER DISTRICT SAVANNAH GA F/G 8/11

GEOLOGICAL AND SEISMOLOGICAL EVALUATION OF EARTHQUAKE HAZARDS A--ETC(U)

MAR 77 W E HANCOCK, E F TITCOMB

UNCLASSIFIED NL

4 OF 5

AD A043849

e. The Low Rank group rocks consist of sericitic phyllite, argillite, quartz-sericite schist, and quartz-sericite gneiss. These rocks are of upper greenschist metamorphic grade. Transition into the High Rank group rocks are lithologies of "Button" mica schist, mica schists with amphibolites and sericite muscovite schist mixed with some chloritic mafic schists. These transition rocks vary from quartz - plagioclase, biotite almandite facies assemblages to staurolite subfacies of epidote-amphibolite facies.

f. The High Rank group rocks are granitic gneiss and metamorphosed ultramafic and mafic rocks. Granitic gneisses include biotite granitic gneiss and quartz feldspar gneiss. Minor amounts of hornblende and quartzite are present. Quartzo-feldspathic assemblages are quartz-microline-plagioclase-biotite-muscovite of the staurolite quartz subfacies. Basic assemblages are hornblende-plagioclase-almandine-epidote or hornblende-plagioclase-epidote of the staurolite quartz subfacies. Metamorphosed ultramafics have diagnostic serpentine, talc, and minor enstatite. Some of the mafic and ultramafic bodies show evidence of retrogressive metamorphism. Granite bodies are generally adamellite. These bodies are implaced during at least two different episodes. Older granites have undergone some epidote alteration and have minor cataclastic texture. The younger granites are not as severely crushed.

g. Granites, gneiss and schists described above make up the Modoc Fault Zone. They are present as tabular to elongated bodies. Foliation and bedding, where observable, strike N55E to N68E dipping steeply either to the SE or NW. Metamorphic grade sharply increases across the zone from low grade to the northwest to high grade to the southeast. Rocks of the Kiokee Belt are of high grades.

h. Figure 3 summarizes the structural relationships. Three hundred structural measurements were taken in 75 localities throughout the zone. One hundred-seventy five joint measurements are analyzed. These measurements are from observations along the South Carolina Clark Hill shores from Parksville to Scotts Ferry and inland. Preferred orientations include N-S, N60W, N30W and N60W trends; all joints are steeply dipping. 1500 joint measurements are compared with 1254 measurements of topographic lineaments and 419 stream trends within the seven county region surrounding the Little River Arm of Clark Hill Reservoir (see Figure 4). Figures 5, 6, and 7 show that joints and foliation strongly control drainage patterns. Lineaments have maxima at N20-35^{o}W and N35-65^{o}E, probably reflecting folds, major rock boundaries, dike concentrations and to lesser extent joint systems following folds. One hundred-seventy lineations and axial traces suggest folding trends of S45W and N45E at 10^{o}N plunge. Populations of joints at N20-40W probably are extension joints resulting from folding and compression; commonly these joints do not offset planor structures (e.g. gneissosity). Shear joints of N-S orientation and vertical dip and N60W of steep dip also are present. These joints have offsets up to 6 inches. Figure 8 is an idealized cross section thru the study area.

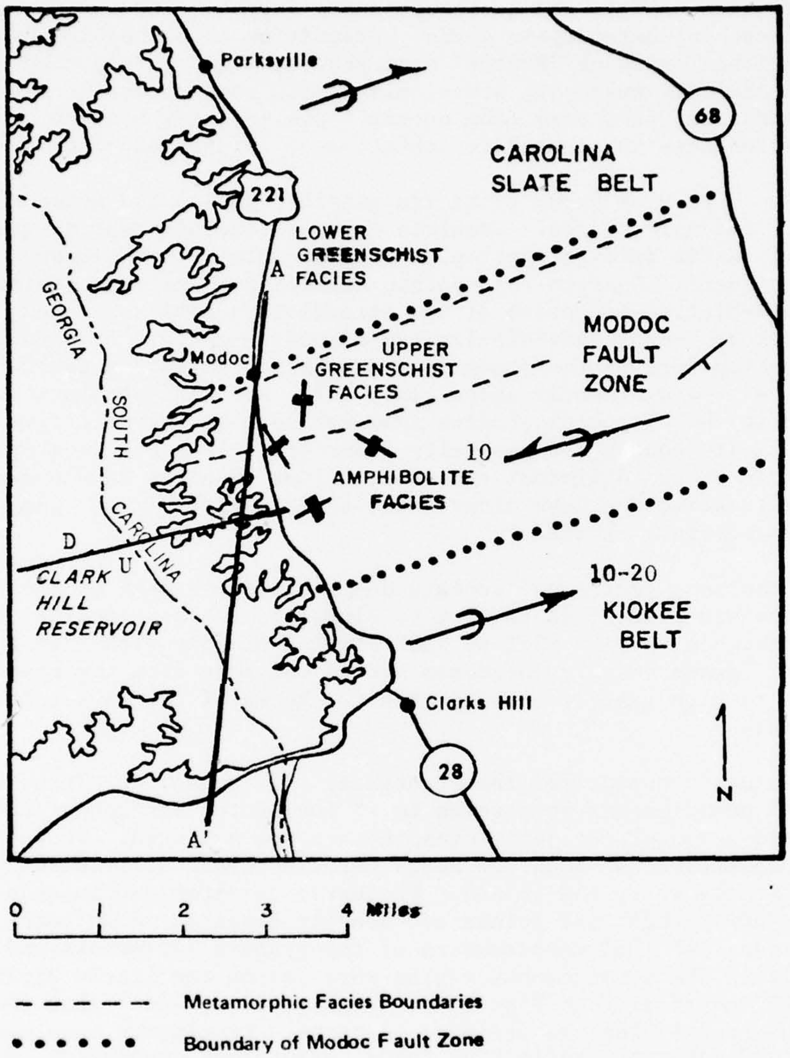
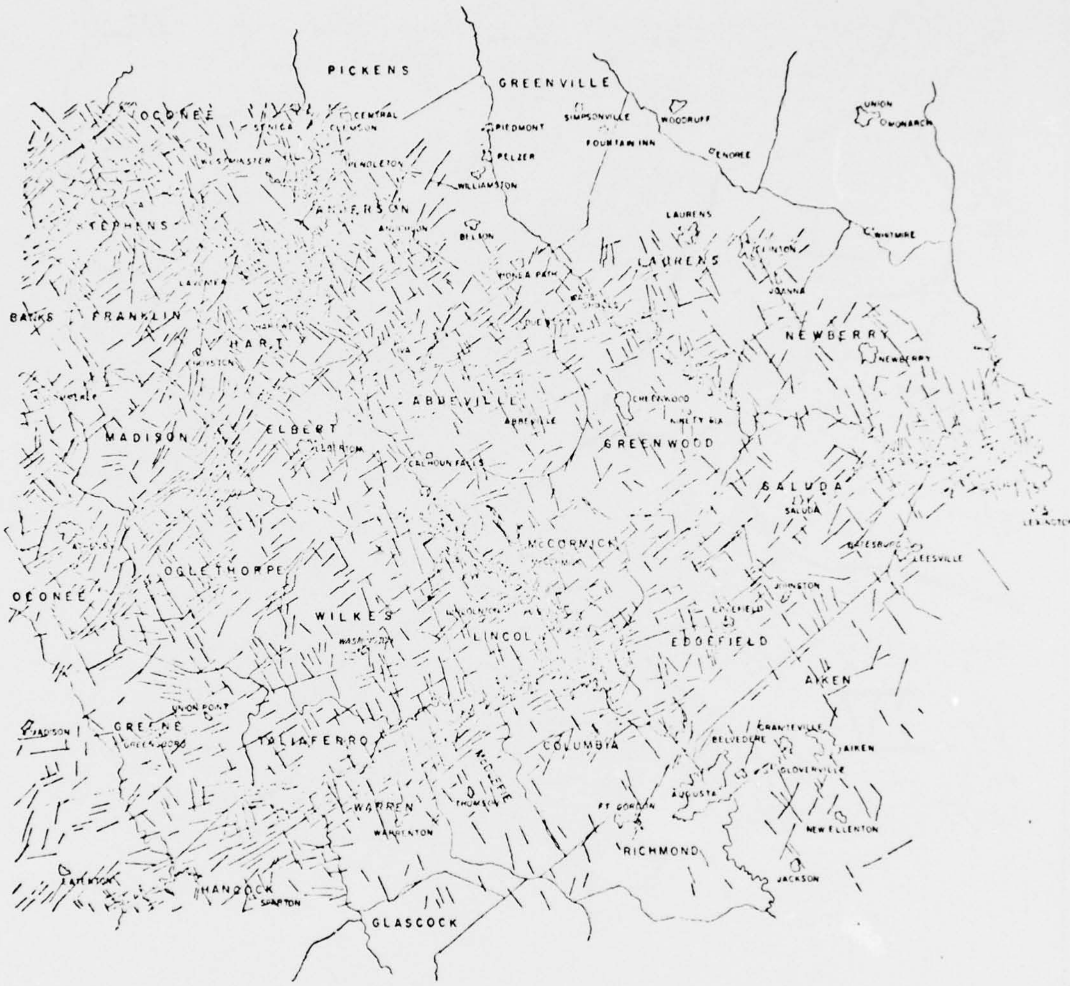


Figure 3 Metamorphic facies across the Modoc Fault zone in South Carolina east of the Clark Hill Reservoir.

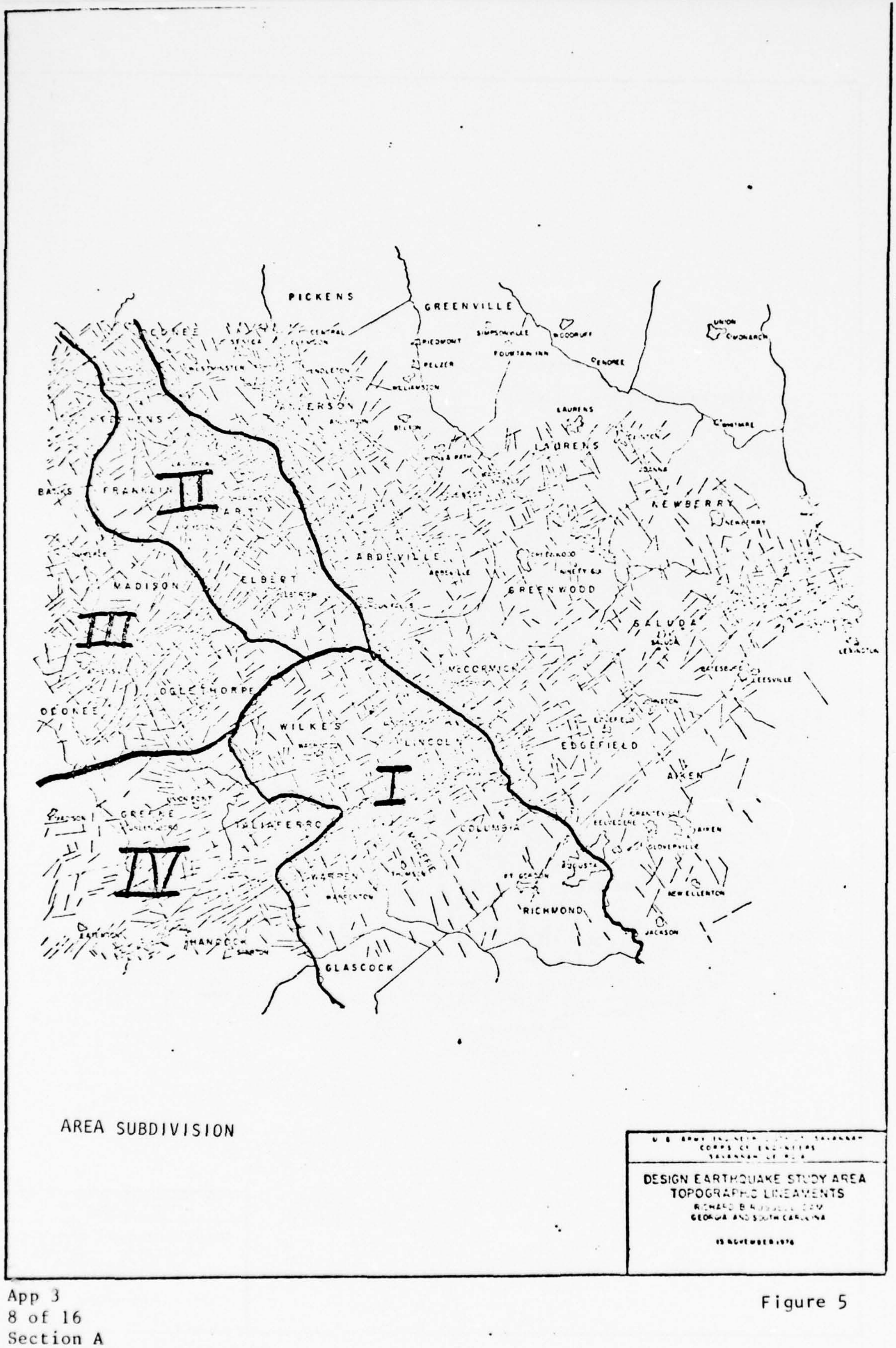


U S ARMY ENGINEER DISTRICT, SAVANNAH
CORPS OF ENGINEERS
SAVANNAH GEORGIA

DESIGN EARTHQUAKE STUDY AREA
TOPOGRAPHIC LINEAMENTS
RICHARD B RUSSELL DAM
GEORGIA AND SOUTH CAROLINA

15 NOVEMBER 1976

Figure 4



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Section A

Figure 5

ROSE DIAGRAMS OF TOPOGRAPHIC LINEAMENTS BORDERING THE SAVANNAH RIVER AREA OF THE GEORGIA PIEDMONT

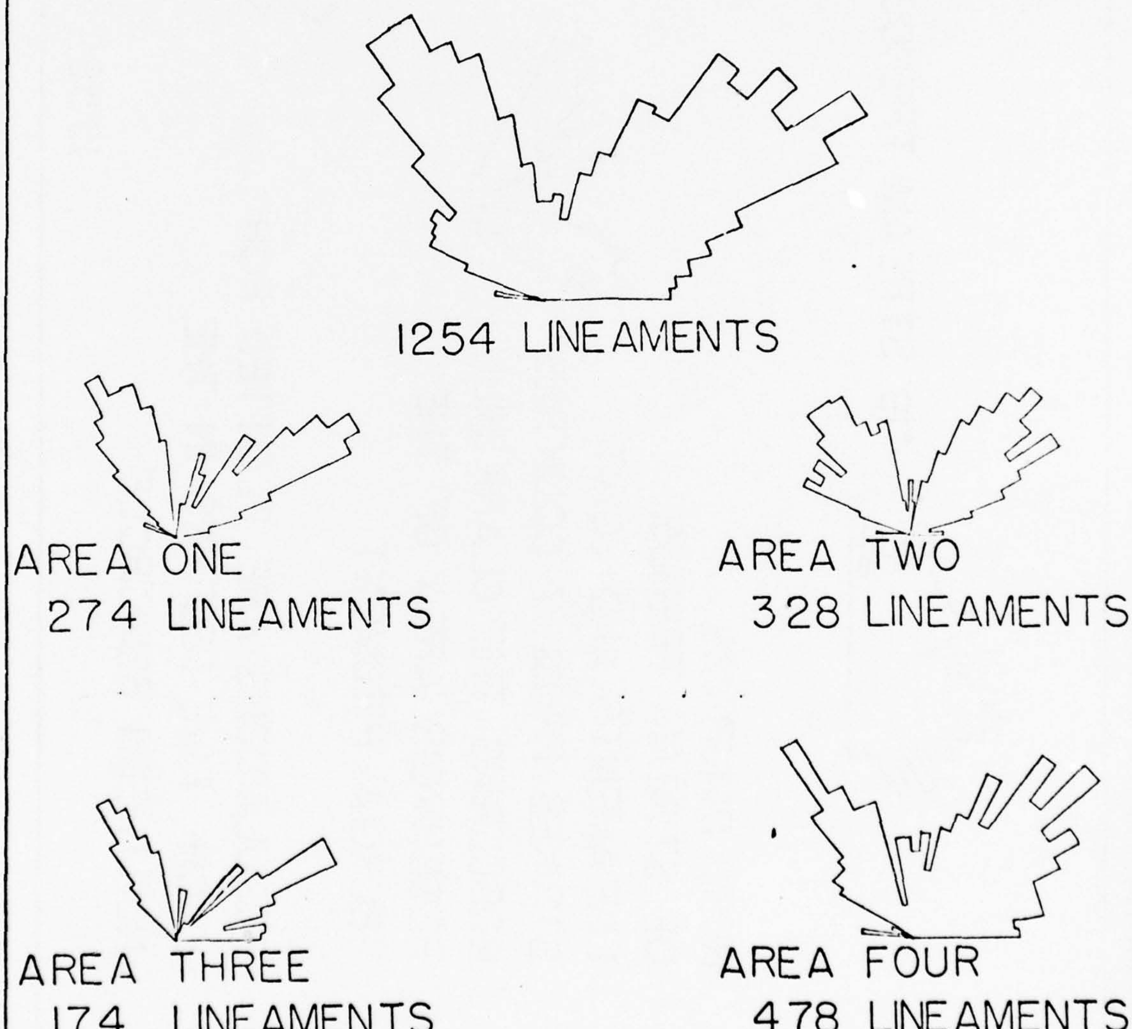


Figure 6

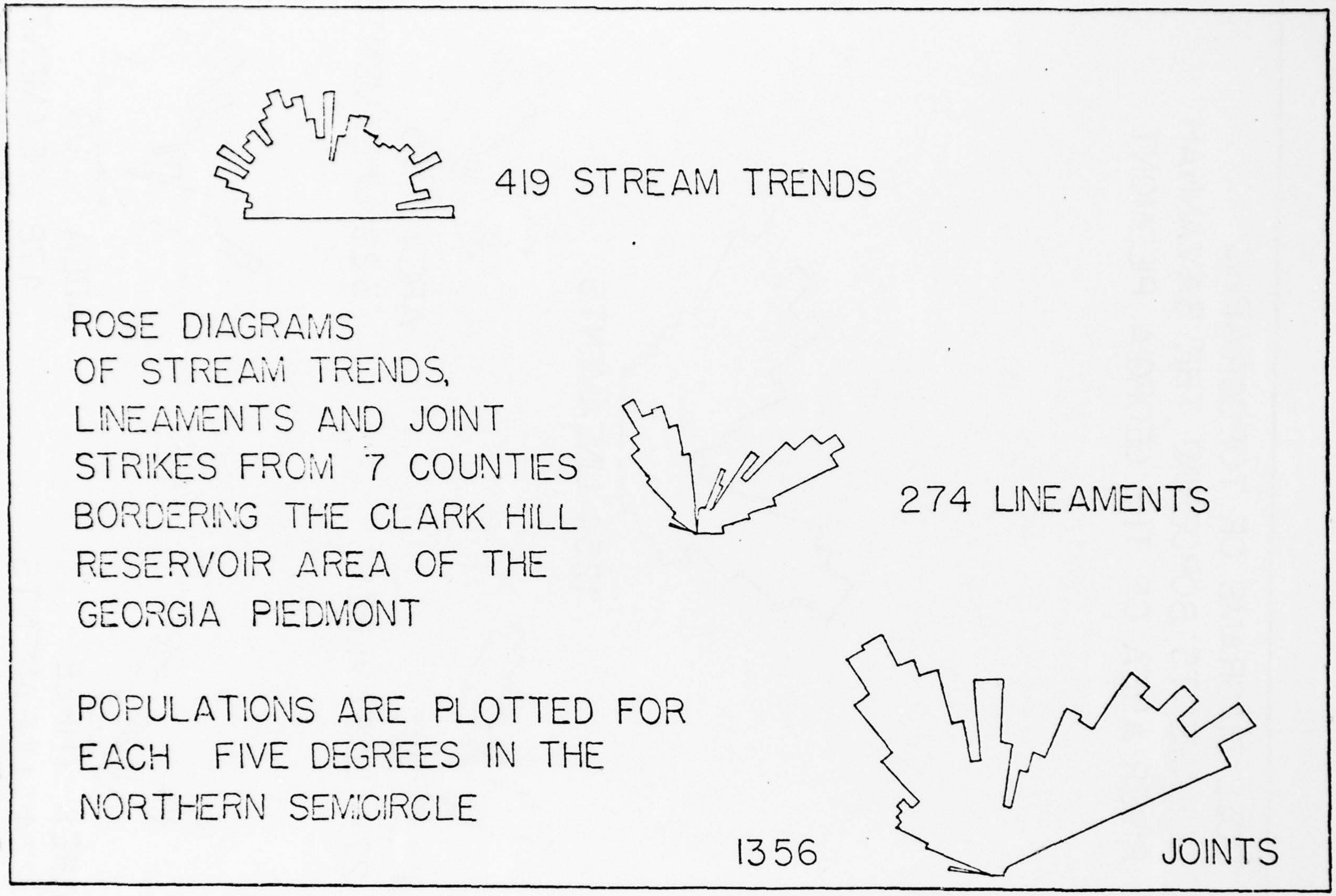
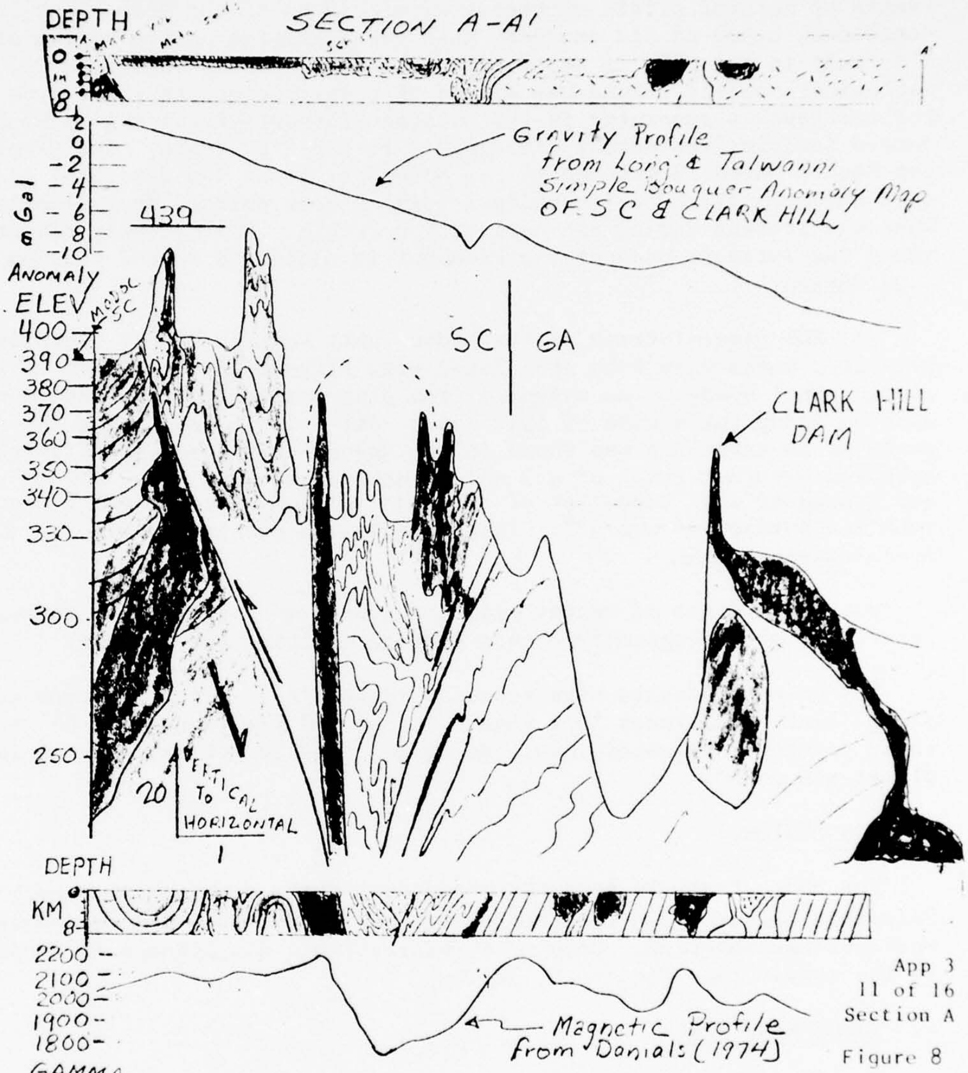

419 STREAM TRENDS
ROSE DIAGRAMS
OF STREAM TRENDS,
LINEAMENTS AND JOINT
STRIKES FROM 7 COUNTIES
BORDERING THE CLARK HILL
RESERVOIR AREA OF THE
GEORGIA PIEDMONT
274 LINEAMENTS
POPULATIONS ARE PLOTTED FOR
EACH FIVE DEGREES IN THE
NORTHERN SEMICIRCLE
1356
JOINTS

Figure 7

Gravity profile and sectional interpretation. Broad linear positive anomalies indicate areas of mafic volcanics in the NW. Trending off the high is less dense metasediments and sericite schists of the Modoc Zone. Small negative anomaly in mid section represent an area of contrasting density interpretated to be a downfolded limb of the suprapositioned Slate Belt rocks. This limb has undergone ductyle deformation and dedensification by granitization due to extreme pressure. Density is similar to granitized and migmatized rocks. Larger negative trends represent granites and felsic gneiss.

Geologic Section based on work gathered in the field by Hancock. Two well defined zones of button schist identify the limits of a broad cataclastic shear zone. Amphibolite and gneiss are downfolded into the limb of the higher grade Kiokee anticline. Granitized gneiss and two episodic granitic intrusion are present in the study area. Ultramific bodies, tabular in nature are present in the Kiokee Belt. Rapidly increasing metamorphic grade produces cataclastic gneiss indicated in Blue. Kiokee Belt-clear; "button schist"-yellow; Gneiss-red; granite - red. High grade amphibolite and gneiss-orange.



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Section A

Figure 8

Magnetic profile and sectional interpretation based on work from Danials(1974) and discussion with Zietz. Smooth broad low on NW identifies the metasedimentary argillites. High identifies quartz-sericite phyllite and "knotty Schist" and thought to be of metavolcanic origin. Linear magnetic anomalies on plan view suggest cylindrical folding about a horizontal axis. The narrow linear magnetic low is equivalent to button schist and interpreted as the trace of the fault. This low corresponds with a radioactive high and is interpreted to be the contact between the Slate Belt and Kiokee belt. Kiokee Belt is characterized by sharp, shorter,& less regular anomalies. A zone of gneissic granit lenses extends southwest from Edgefield Co. and produces a radioactive high, this high also marks other felsic gneiss along the edge of the slate belt and a porphyroblastic gneissic granit. Radioactivity profile not shown Gold-Slate Belt Rocks; yellow-"button and knotty schists; red-granite& gneiss;clear-Kiokee Belt green- ultra mafics and chlorite schists

i. The Modoc Fault Zone has been questionably linked to recent earthquake activity by Howell and others. (See trip report dated 20 July 76, SASEN-FG, Memorandum for Record). Long and Denman in 1973 and 1974 conducted seismic surveys in the Little River Arm of the Clark Hill Reservoir (CHRA). Eighty-five days of low noise recordings were obtained with nine events of natural origin occurring within 20 km of the Modoc Zone. Long concluded, based on his studies, that the suggested active status of the old fault in the CHRA is not firmly established. See Guidebook 16, Georgia Geological Society. Long has agreed that an appropriate fault type and depth for earthquakes generated in the present Piedmont stress regime would be reversed faulting and normal faulting at from 0-8 km depth. See Memorandum for Record dated 19 October 1976. Moreover, it is now generally accepted that extensional and compressional couples have shifted dramatically from what was present during the Appalachian origin. Geologically recent features since the Jurassic suggest the Piedmont is subjected to NNE tension and E-W compression.

j. The general trend of the Modoc Fault Zone is N68^{o}E. Ductile folded mylonitic zones have been associated with slip-strike faults by investigators in the past; however, no evidence from slip-strike faulting was found in field studies along the strike of this zone. One brittle failure in the crestal parts of an anticline was found in the Modoc Fault Zone (see Figure 3). This produced a thrust fault of a 3 mile length whose fault line strike was N71E and dipped 42^{o}SE. Lineation of slickensides indicated movement along N40^{o}W from the horizontal was 43^{o}. This movement is consistent with the Paleozoic Appalachian orogin.

k. No evidence of recent ground rupture or geomorphic features characteristic of geologically recent surface faulting are present.

l. No other faults were found or identified. Offset in rock structure along joints was always less than 6 inches and are thought to be related to shear joints of Paleozoic age. No evidence of recent activity along joint planes was found.

7. CONCLUSION:

The Modoc Fault is best described as a ductile Mylonitic Zone. Ancient Paleozoic features are seen throughout the zone. No recent evidence of movement was observed. Only minor microseismic disturbance is found presently in the zone. (See Figure 9, 10 .)

8. RECOMMENDATIONS:

Further study of the zone should be conducted when and if a Design Earthquake and Hazard Risk Analysis is to be conducted for Clark Hill Reservoir.

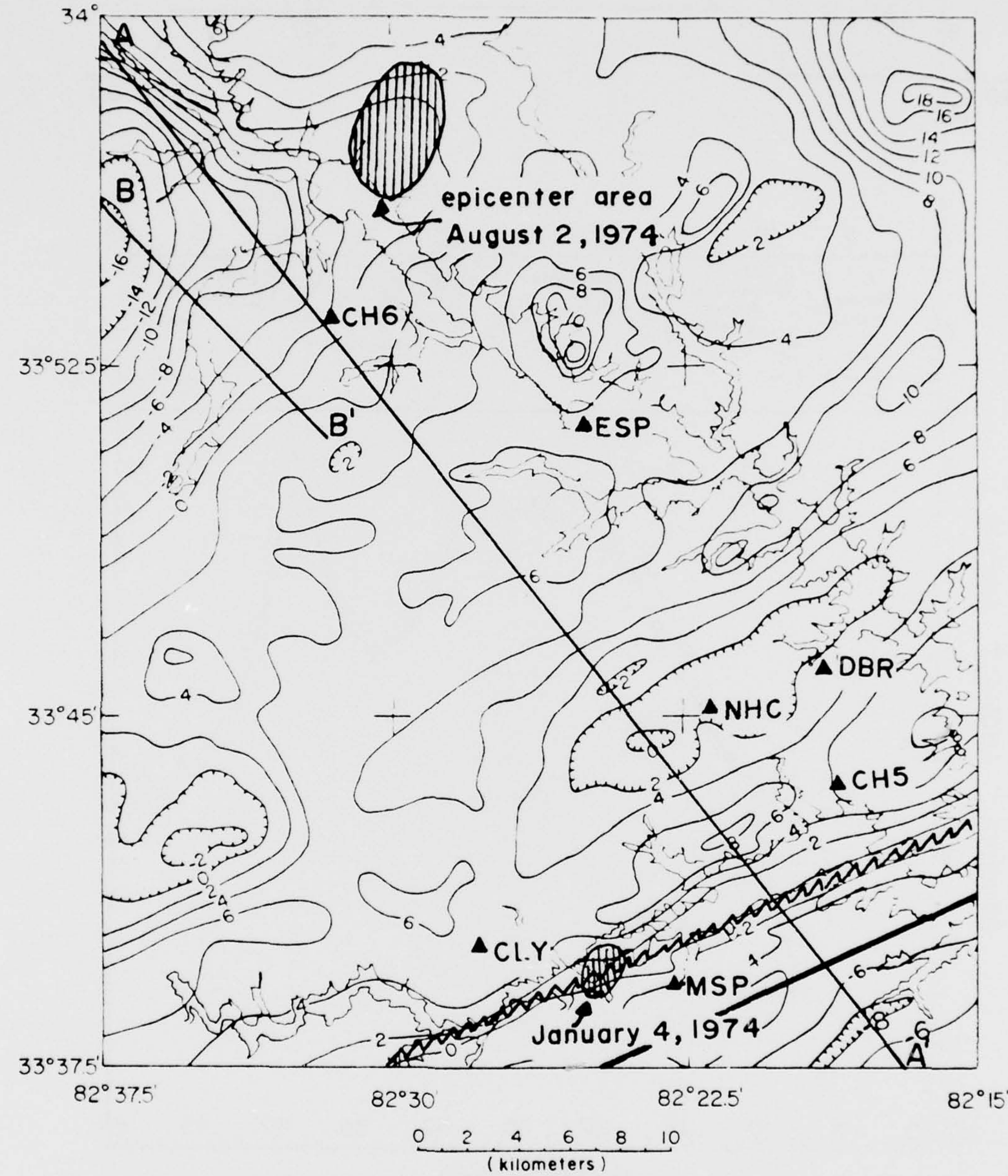

Figure 9. Index map showing relation of gravity to seismic recording sites, epicenters and modeled profiles. The solid line in the southeast quadrangle denotes the Kiokee belt - Carolina slate belt boundary (Daniels, 1974). The saw tooth line denotes the Modoc Fault (?) as shown on geologic map of Georgia (1976).

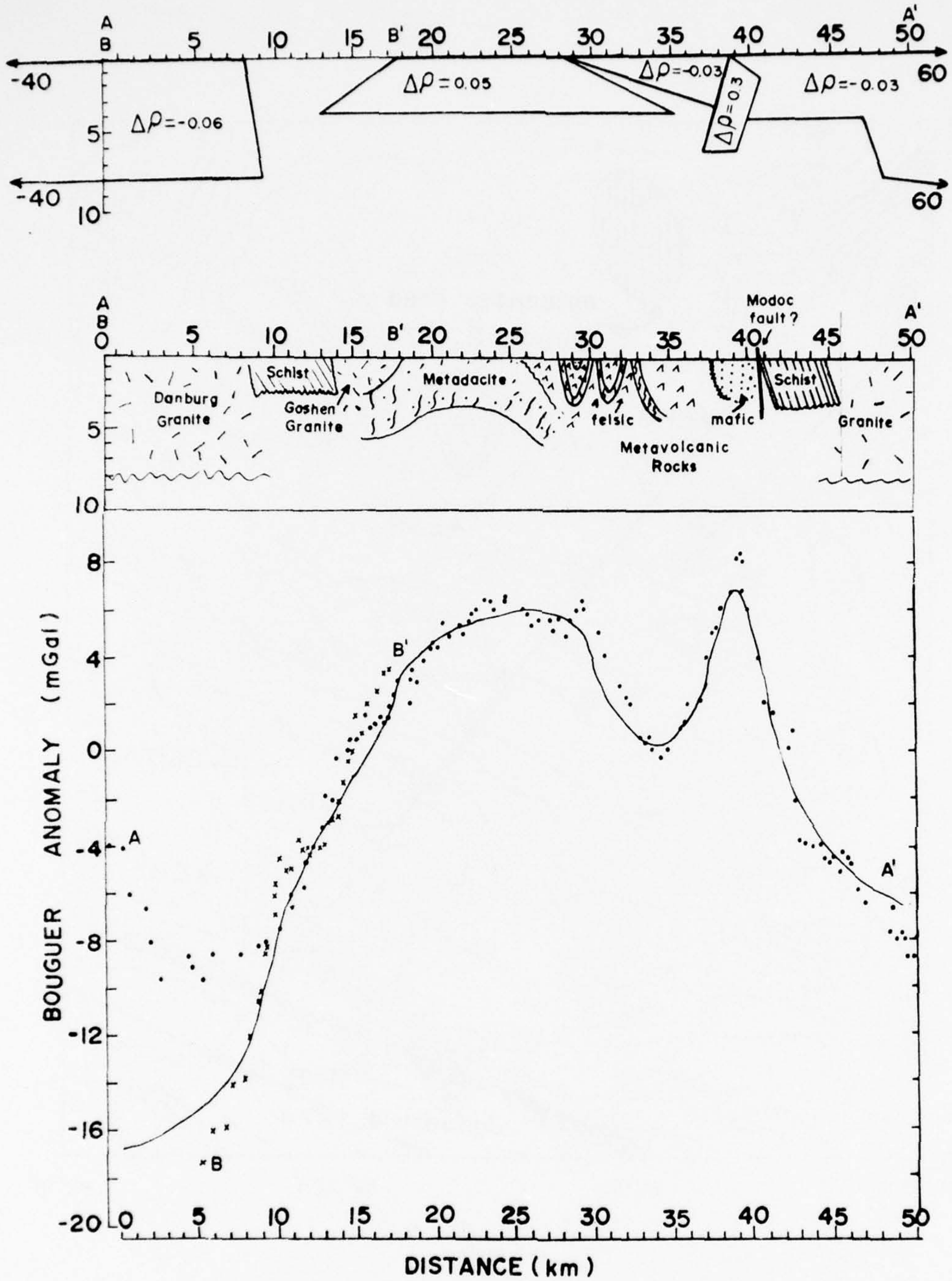

Figure 10. Profile AA′ showing model used to explain Bouguer anomalies and hypothetical geological structure based on gravity model.

This study could include a one year tripartite microseismic monitoring program, age dating of the most recent demonstratable movement and establishment of the cataclastic gradient by a series of thin section analysis across the feature.

William E Hancock

10 Incl
as

WILLIAM E. HANCOCK
Geology Section

SASEN-FG (4) 31 August 1976

SUBJECT: Trip Report to Modoc, South Carolina

MEMORANDUM FOR RECORD

1. DATE: 20 July 1976

2. PURPOSE: To inspect and evaluate the proposed Modoc fault zone located east of Clark Hill Reservoir and assess its relationship in the seismic risk study and design earthquake for Richard B. Russell.

3. PERSON MAKING TRIP:

William E. Hancock, Geologist, SASEN-FG

4. PERSON CONTACTED:

David Howell, Geologist, State of South Carolina Development Board

5. OBSERVATIONS:

a. Howell and Pirckle, representing the State Development Board, proposed the existence of the fault in 1973. Low level seismic events *(Note 1) identified with the fault zone include Clark Hill Events, Columbia, Edgefield, Modoc and McBea. With the exception of the Clark Hill events, these epicenters generally occur in excess of 18 miles from the dam (Clark Hill).

b. The expression of the Modoc fault zone in the vicinity of Clark Hill on the South Carolina side is found in field expression of:

(1) A westward increasing metamorphic gradient within the Carolina Slate Belt rocks. Green schist at Parksville - Amphibolite at Belgrave Baptist Church.

(2) A westward increasing deformational gradient, from an undisturbed meta argellite at Parksfield to blasto myfonitic gneiss at Modoc Camp 8.

c. The fault zone as observed along Clark Hill Reservoir is similar in nature to the Brevard throughout Georgia, South Carolina and North Carolina, and the Goat Rock and Towaliga fault zones in Alabama and Georgia. The zone around Modoc is of lesser extent than the above, about one mile wide at its location at Clark Hill. There was no ground evidence to assess its capability at the observed positions. The proponents of (Note 2) this zone wish now to connect the Modoc with the Goat Rock Fault and Lake Murry fracture. This will enable them to propose a length from Virginia to the onlap at the southeast terminus of the Piedmont.

* Note 1. Howell and Pirckle propose this relationship, Per. Com.
* Note 2. Howell (1976), Major Structural Features of South Carolina, Geol. Soc. of America Abs. with Programs, Vol 8, No. 2, pages 200-201

6. CONCLUSIONS:

a. A Brevard type zone of cataclastic rocks exist east of Clark Hill dam site.

b. Its capability for Earthquake generation can presently be accessed only on related historic earthquakes falling on its trace.

c. There is no field evidence of recent movements at known outcroping locations.

d. Observations - Triassic diabase dikes cut across bedding and lineation at the site on Clark Hill. Therefore, this fault zone is presently termed a Paleozoic fault with dip slip and strike slip components of movements demonstratable along sections which can be related to the Clark Hill exposures. The fault can be considered to possess a near critical remnant stress field with a possible additive factor due to isostatic rebound of the Piedmont. As such, low levels of seismicity can be expected and are historically demonstratable along its geographic position. (i.e. McBea, 1959 Oct 6 Io-VI, Batesburg 22 Sep 68 Io-IV).

7. RECOMMENDATIONS:

a. Ten (10) day field study of the zone. Limit of geography would be that which falls within the 50 mile radius of the Richard B. Russell study.

b. A period of monitoring for microseismicity on the zone around Clark Hill.

c. Renew study, possibly with financial contribution to outside investigators when the Clark Hill Dam is subject to a seismic risk study.

William E. Hancock
WILLIAM E. HANCOCK
Geology Section

SECTION B

Geologic Report on The Area in the Western Portions of the Proposed Richard B. Russell Lake

10 February 1977

GEOLOGIC REPORT OF THE AREA IN THE WESTERN PORTIONS
OF THE PROPOSED RICHARD B. RUSSELL LAKE

1. The subject of this report is The Geological Hazards and Seismic Risk Studies in the Northwestern Portions of the Proposed Richard B. Russell Lake.

2. This report is the result of studies conducted during periods 1 October thru 10 November 1976.

3. Persons making the study were William E. Hancock, Geologist, SASEN-FG and Daniel Waltz, Hydrologist, SASEN-FG.

4. The following persons were contacted for outside information:

Villard Griffin, Professor of Geology, Clemson University
David Howell, Geologist, South Carolina State Development Board

5. Comments and observations resulting from the study follow:

a. The field study of geologic hazards and faulting was conducted during a period of six weeks in the Fall of 1976. Specific site studies such as Patterson Branch and Richard B. Russell Dam site are subjects of separate report. This study covers a land area from Hartwell Dam southeastward to Parksville, South Carolina and is restricted to counties adjacent to the Savannah River in the state of South Carolina. The study was conducted in reconnaissance fashion with detail mapping conducted only along the South Carolina shores of Clark Hill Lake. Excellent geologic coverage was available from the work of Dr. Villard Griffin between areas of Hartwell Lake and McCormick County in South Carolina. These geologic maps were used at face value. Field checking of major geologic structures and faults were conducted when their location fell in close proximity to Russell Dam. Figure 1 locates work done during the Fall of 1976.

b. Figure 2 shows the general geology of the study area. The geology represented is drawn heavily from the mapping done by H. Johnson in Edgefield and McCormick Counties, William Hancock in Clark Hill area and McCormick Counties and the before mentioned Villard Griffin.

c. See accompanying map for lithologic description.

d. The lithology can be divided into 3 belts. These belts are the Slate Belt rocks of Carolina, the Charlotte Belt and the Inner Piedmont. Metamorphic rank is the distinguishing field characteristic used.

e. Commonly, the stratigraphy is ordered from the oldest Inner Piedmont to the younger overlying Charlotte to the still younger Slate Belt rocks. This stratigraphy generally ranges in age throughout Paleozoic time.

f. Complex structure is seen in conical and cylindroidal folding of mesoscopic and regional scale. Zones of shear are present and are noted on the geologic map Figure 2. Most conspicuous shear features are found in the Lowndesville Belt. This zone divides the granitoid gneiss of the Charlotte Belt from the schistotic and migmatitic Inner Piedmont. The Lowndesville Zone is similar to the Brevard and Modoc Zone.

g. Outside of the Patterson Branch Fault and the Diversion Channel Fault, no large scale faulting was found. The above faults are subjects of separate memorandum and discussion. Multiple small faults are found but are of limited ground extent and consequence. No evidence of recent movement on any fault investigated was found. Geologist contacted in the state of South Carolina reported that they have found no evidence of recent movement in faults uncovered in their investigations.

6. CONCLUSIONS:

The study presented in this report found no geologic hazard or active faulting in the area investigated. The scope of the study is felt to be adequate when viewed in the context of the intensive investigations of other investigators.

FIELD STUDY OF THE GEOLOGY AND FAULTING IN THE RICHARD B. RUSSELL AREA

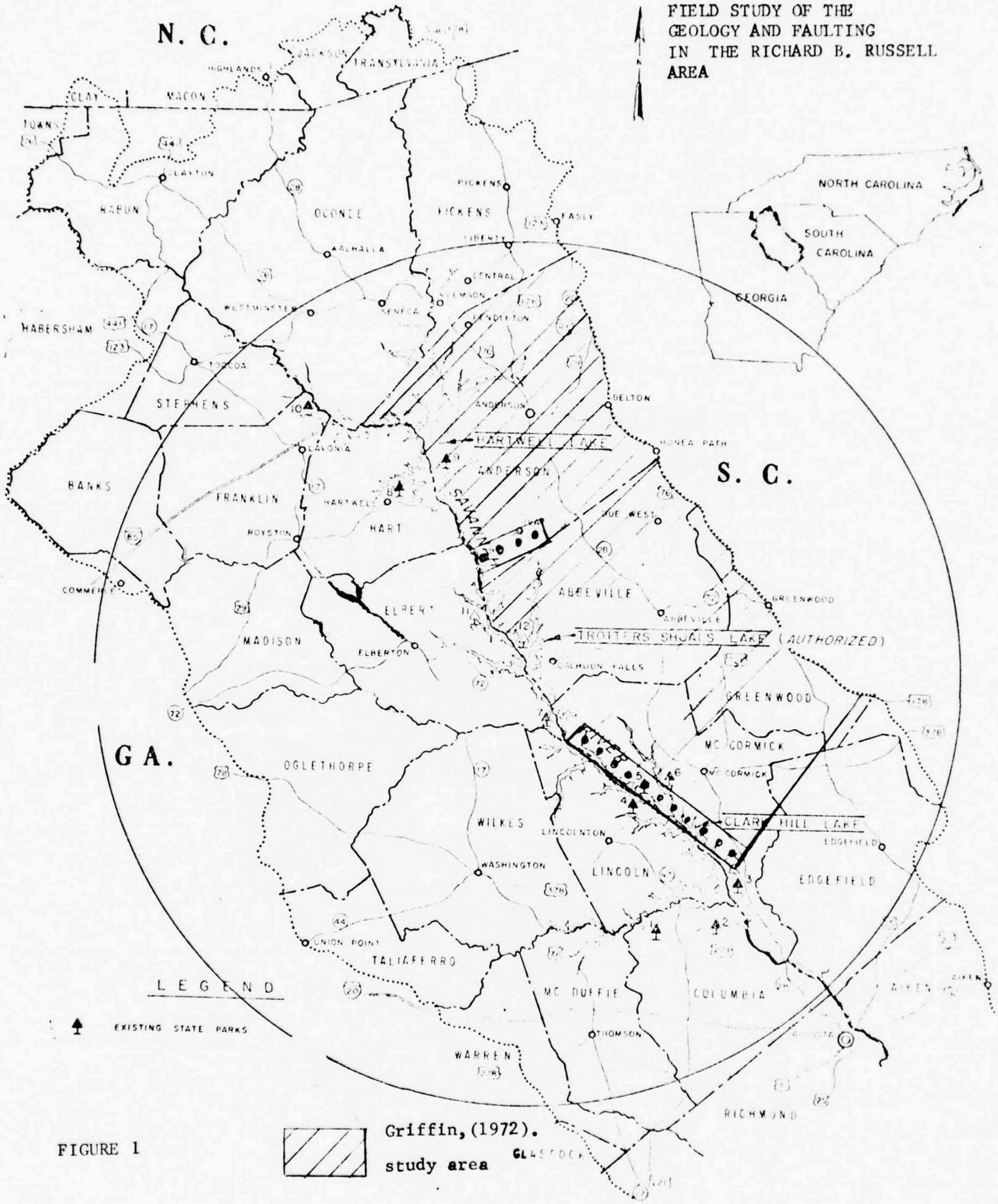

FIGURE 1

Griffin, (1972). study area

Area studied in detail by this report

For Figure 2 see general Study map

in pocket

SECTION C

Skylab 4- Photographic Study

R.B.R.
Fault Study File

In an effort to determine if there were any faults in the area of the proposed Richard B. Russell Dam that might be related to seismic activity, a study was made of an enlargement of a photograph which was taken on 30 November 1973 by Skylab 4. The photograph covers an area 90 by 90 miles. The Savannah River is running down the central part of the photograph, the Hartwell Reservoir at the top, and the city of Augusta at the bottom. At the eastern edge of the photograph is lake Greenwood , in South Carolina, and at the western edge is lake Sinclair, in Georgia. Interstate highway 20 is seen running from the the southeastern corner to the northwestern corner of the photo.

The photograph covers the Georgia, and South Carolina Piedmont, and Coastal Plains. The border between the Piedmont and Coastal Plain is marked by a well defined dendritic drainage pattern to the southeast. This border between the Piedmont and Coastal Plain closely parallels a northeast-southwest trending lineament which runs from approximately 10 miles east of Saluda, South Carolina to Lake Sinclair, north of Milledgeville, Georgia. This lineament on the South Carolina side of the river was pointed out by Griffin[1] in a previous Skylab mission photograph. There are two other lineaments that parallel this one, one just southwest of Saluda, South Carolina, and one about four (4) miles southeast of Greenwood, South Carolina.

There are two more lineaments running in an almost north-south direction; one located about eight (8) miles north of Calhoun Falls, South Carolina, and the other about eight (8) miles north of Abbeville, South Carolina.

[1] Griffin, Villard S. Jr., GEOLOGIC NOTES, Volume 18, Number 2, 1974. "Skylab Photograph of the South Carolina Piedmont: A Preliminary Analysis"

A study was also made of the same general area using a LANDSAT (ERTS) photograph. This photograph, which covers an area of 115 miles by 115 miles was taken by LANDSAT-1 on 25 February 1975. LANDSAT flies in a circular orbit 570 miles (920 km) above the earth's surface and circles the earth every 103 minutes.

The photograph covers the Blue Ridge province of North Carolina to the northwest, and the Piedmont area of Georgia, and South Carolina as for south as the Clark Hill Reservoir.

The most striking feature on the photograph is the Brevard fault zone, which runs form Gainsville, Georgia in the south-west to the top central part of the photo. The Warwoman shear zone also shows up very clearly trending north-east, crossing the Brevard fault zone near lake Jocassee. There are numerous lineaments between these two fault zones, including the Tallulah Falls Dome to the southeast.

There is a lineament, approximately 40 miles along, about 5 miles south of Greenville, South Carolina that curves south-westward toward the Savannah River. This lineament intersects another that trends north-west, south-east between Anderson, South Carolina and Abbeville, South Carolina.

In the extreme southeast of the photograph coverage is a lineament that trends southwest, northeast. This lineament also shows-up on the Skylab photograph mentioned above.

CONCLUSION

Because of the deep weathering and vast vegetative cover of the Piedmont area, it is difficult to detect the underlying structural features using the LANDSAT, and Skylab photographs. It should be noted that for a more accurate and detailed analysis of the area, a study should be made using the more conventional 1:20,000 scale, aerial photographs.

SECTION D

DIVERSION CHANNEL FAULT STUDY

DIVERSION CHANNEL FAULT STUDY

SASEN-FG 7 September 1976

SUBJECT: Trip Report - Richard B. Russell Project

MEMORANDUM FOR RECORD

(Deleted Portions of Memorandum Deal With Subject Matter Other Than That Necessary for Consideration in This Study.)

1. DATE: 16-20 August 1976.

2. PURPOSE:

a. Investigate geologic structure extending through the diversion channel between Stations 14+00 (riverward side) and Station 21+75 (landward side) as reported by Construction Division on 11 August.

b. OMITTED.

3. PERSON MAKING TRIP:

Robert G. Stansfield, EN-FG

4. PERSONS CONTACTED:

a. Corps of Engineers Personnel

(1) Captain Melvin Lynch - Richard B. Russell Project
(2) Mr. Bob Stephens - Richard B. Russell Project Geologist
(3) Dr. James Erwin - SAD Division Geologist
(4) Mr. Allen Platt - SAD - Chief, Construction Branch
(5) Mr. William Hancock - SASEN-FG - Geologist
(6) Mr. Jack Keeton - SASEN-FG - Geologist (Chief, Drill Crew)

b. Non-Corps of Engineers Personnel

(1) Mr. James Trammell - Southeastern Highway Contractors - Project Supt.
(2) Mr. Douglas Hudson - Gentry & Thompson, Inc. (Bridge Subcontractor)
(3) Mr. Malcolm Vest - Davidson Mineral Properties
(4) Mr. James Voss - Gulf Oil Corp. (Drilling and Blasting Subcontractor)

5. SUMMARY:

a. A sericite (mica) - feldspar dike, emplaced along a Triassic or post-Triassic age fault, strikes across the diversion channel from 14+00 to 21+75.

The average strike of the dike and fault is approximately N. 10°E. with a westerly dip of approximately 50 degrees from the horizontal. The location of the dike is shown on the attached plan view of the diversion channel.

b. OMITTED.

6. OBSERVATIONS:

a. OMITTED.

b. OMITTED.

c. OMITTED.

(1) OMITTED.

(2) OMITTED.

(3) OMITTED.

(4) OMITTED.

d. OMITTED.

e. OMITTED.

f. (1) Investigation of the geologic structure in the diversion channel excavation was made at various times by me from the afternoon of 16 August thru the morning of 19 August. I was accompanied by Bob Stephens the afternoon of 16 August, by William Hancock the afternoon of 17 August, and by James Erwin and Allen Platt on 18 August. By phone on the morning of 18 August, I obtained the following petrographic and x-ray defraction analysis results from Dr. James Neiheisel (SAD Lab) that he had just completed for us on a sample of the dike material: 60% feldspar (predominantly potassium feldspar) 39% sericite (mica), 1% magnetite and a trace of kaolinite.

(2) The structure consists of a 2 to 6 foot thick, altered-feldspar rich dike extending from the west sideslope of the Diversion Channel at Station 21+75 to the east sideslope at Station 14+00. Between approximate Station 18+00 and 14+50, the feldspar dike was covered by overburden or material disturbed by excavation operations and therefore could not be observed in this section. The feldspar dike dips westerly at approximately 50 degrees from the horizontal and exhibits an average strike of N. 10°E. within the limits of the Diversion Channel. This average strike is determined from two surveyed locations on the footwall of the dike: elevation 377.4 on the centerline at Station 18+95 and elevation 387.7 at 107 feet right of the centerline at Station 20+60. The local strike of the footwall of the dike at approximate Station 20+50 is N. 25°E. with a westerly dip of 55 degrees; at Station 18+95 the local strike is N. 8°E. with a westerly dip of 48 degrees.

At its exposure in the channel sideslopes at Stations 21+75 and 14+00, the dike is truncated by overlying soil horizons approximately 4 feet in thickness.

(3) The 2 to 6 foot thickness of the dike is estimated primarily from its exposure in the sideslopes, as excavation by dozer has removed most of the width of the dike exposed elsewhere in the excavation. The country rock on both sides of the dike consists of porphyritic meta-dacite and northeasterly trending meta-diabase dikes. However, the country rock on the westerly side of the dike is deeply weathered to saprolite, while the country rock on the easterly side is weathered to a much lesser depth. At the time of this inspection, excavation on the westerly side had progressed to within 15 to 20 feet above invert grade between approximate Station 19+50 and 18+00. This was as much as 40 feet deeper than in the harder country rock on the easterly side of the dike. Thus, the footwall of the feldspar dike was well exposed between approximate Station 20+60 and 18+00, although water collected in the bottom of the deeper excavation.

(4) The dike rock encountered was friable or soft to moderately hard, very fine grained, and white colored or white with a light green or pink tinge. The rock with the light green tinge is generally moderately hard. All the dike rock is intensely jointed with joints extending into the dike rock from the country rock. There is a faint foliation parallel to the footwall. In some areas, planes of mineralization, probably epidote, commonly occur within inches of (and parallel to) the footwall. These mineralized surfaces are relatively smooth and in some instances, the mineralization exhibits a faint appearance of vertical parallel lineation. Manganese dioxide staining of joint surfaces, and into the dike rock itself, is widespread. At two locations where the footwall contact of the dike with the country rock could be observed in cross-section, and along the observed upper surface of the footwall, the contact appeared distinct with no visual evidence of brecciation or separation.

(5) The country rock on both sides of the feldspar dike consists of the same type, porphyritic meta-dacite cut by near vertical meta-diabase dikes that generally strike northeasterly and are 1 to 4 feet in width. (As already described, the rock on the west side of dike is weathered to a much greater depth than the rock on the east side.) A total of 4 of these meta-diabase dikes were observed striking across the channel excavation between approximate Station 21+50 and 18+00. However, none of those meta-diabase dikes cross the feldspar dike; i.e. the meta-diabase dikes are truncated at the feldspar dike. Two of these meta-diabase dikes enter the excavation from the west slope in the vicinity of Station 18+00 to 18+50. The other two meta-diabase dikes, entering from the east, truncate at the feldspar dike's footwall at approximate Stations 21+50 and 20+10.

The 4 foot wide meta-diabase dike (at approximate Station 21+50) contacts the footwall of the feldspar dike in the final sideslope on the west side of the channel. At this contact the meta-diabase dike appears to curve to the south by about 3 to 4 feet; i.e. the diabase dike appears to have been dragged to the south at the footwall contact.

(6) Dr. James Erwin inspected the feldspar dike structure on 18 August and uncovered several smooth surfaces within the feldspar dike material that were lightly striated with vertical striations. The surfaces were oriented parallel to the footwall and were mostly located on the upper portion of the footwall slope between Stations 20+10 and 19+50. They were within inches of the feldspar dike - country rock contact. Dr. Erwin also discovered the one foot wide meta-diabase dike at approximate Station 20+10 and pointed out the following two features associated with it: (1) a polished surface of manganese dioxide staining on an exposed joint surface in porphyritic - meta-dacite rock at its contact with the meta-diabase dike near the east sideslope of the channel excavation (2) numerous small slickensided surfaces within weathered meta-diabase dike material at the footwall contact with the feldspar dike. (At this footwall contact the meta-diabase was weathered or altered to a brown colored clay-like material having a firm to stiff consistency.) We also observed a feature consisting of 4 curvilinear ridges on the upper portion of the footwall slope at approximate Station 19+50. The ridges were approximately 1/4 inch high by 1 inch wide and were spaced 6 inches apart. They were approximately 3 feet in length and curved upward, from an imaginary horizontal line, at an average angle of approximately 30 degrees.

7. <u>CONCLUSIONS</u>:

a. The feldspar rich dike has apparently been emplaced along a fault of Triassic or post-Triassic age which had a lateral slip component of direction. This is evidenced by the northeasterly trending meta-diabase dikes (generally believed to be of Triassic age) being truncated by the feldspar dike. The indication of southward drag of the meta-diabase dike at Station 21+50 could have resulted from a right lateral slip fault.

b. No evidence was found that the fault is geologically young or active. No breccia zones were found and there is no topographic evidence at the site of faulting as might be found from an active fault. Also, the 4 foot thick soil horizon shows no evidence of offset and has taken a considerable period of time to form that thickness.

c. The evidence found by Dr. Erwin and reported in subparagraph 6.f.(6) above could be evidence of movement within the feldspar dike after its emplacement.

SASEN-FG

7 September 1976

SUBJECT: Trip Report - Richard B. Russell Project

RECOMMENDATIONS:

a. OMITTED.

b. OMITTED.

c. When the excavation in the Diversion Channel is completed to grade along the feldspar dike and fault, EN-FG should perform exploratory borings and hydraulic pressure tests along its strike in the Channel.

d. Dr. Neiheisel (SAD Lab) should personally select samples of the country and dike rocks and soil overburden for laboratory analyses in an effort to date the dike and determine the strain history of the rocks. (Dr. Neiheisel and E. Titcomb have visited the project in order to obtain samples for such purposes and testing is currently underway.)

3 Incl
as

ROBERT G. STANSFIELD
Geology Section

CF:
SADEN-F
EN-FS
EN-CP, ATTN: Mr. Harward
CD-S
CD-CO (2 copies - 1 copy for
R. B. Russell Field Office)

DISPOSITION FORM

For use of this form, see AR 340-15; the proponent agency is The Adjutant General's Office.

REFERENCE OR OFFICE SYMBOL	SUBJECT
SADEN-F	TRIP REPORT - Richard Russell Project

THRU: Chief, F&M Branch | FROM James W. Erwin | DATE 20 Aug 76 | CMT 1

TO: Chief, Eng Div | Dr. Erwin/cpd/6704

1. Purpose: To inspect possible fault across diversion channel.

2. Place & Date: Richard Russell Project, 19 August 1976.

3. Persons Attending:

Robert Stephens	Project Office
Robert Stansfield	Savannah District Office
Allan Platt	SAD
James Erwin	SAD

4. Synopsis: A large fracture zone trending across the diversion channel excavation has been exposed by the excavation. There are indications that movement has occurred along this fracture in the geologic past, thereby classifying it as a fault. The fracture zone separates deeply decomposed rock encountered in the middle third of the channel from hard rock encountered in the downstream portion. My preliminary observations indicate the fault to have been inactive for a substantial length of time.

5. Observations:

a. There is a large rock fracture zone extending diagonally across the diversion channel from station 14+21 on the river side to station 21+75 on the land side. The fracture zone strikes approximately N 8° E and dips approximately 50° NW. The shattered rock zone is about 5 feet thick.

b. There is evidence that movement has occurred on the fracture zone, thereby classifying it as a fault. This evidence consists of intrusive dikes which are truncated at the fault, one dike which has a drag fold apparently caused by movement on the fault, and striations and polishing of the fault surface. Another indication is the thinly plated condition of the rock just behind the fracture surface.

c. This fault was not unexpected. During subsurface investigations for the diversion channel, it was noted that excessively deep alteration or decomposition of the rock existed in the middle third of the channel while hard rock existed in the downstream portion. The deep decomposition was thought to be the result of faulting. This appears to be the case. The fault forms the contact between the downstream hard rock and the upstream soft rock. See pictures in the attached folder which show this contact.

d. Another smaller fault trending generally perpendicular to the large fault was observed during the inspection. This fault parallels and is contained within one of the diabase dikes which is truncated by the larger fault discussed above. There is no change in quality of the rock from one side of this small fault to the other.

e. My preliminary observations of the main fault indicate that it is inactive. There is a soil layer overlying the fault which has not been disturbed by movement on the fault. This soil layer is about 5 feet thick and required many thousands of years to develop. Any recent movement on the fault would have disturbed this soil

DA 1 FEB 62 2496 REPLACES DD FORM 96, EXISTING SUPPLIES OF WHICH WILL BE ISSUED AND USED UNTIL 1 FEB 63 UNLESS SOONER EXHAUSTED.

☆ U.S. GPO: 1974-558-130/8645

6. Conclusions & Recommendations:

a. Present indications are that the fault is inactive; however, it must be studied in detail to confirm this inactivity.

b. The fault trends diagonally across the right earth embankment. The fractured rock in the fault could serve as a seepage conduit beneath the dam unless properly treated. The District should investigate this with borings while the area is readily accessible and then make provisions for the necessary treatments.

J. W. Erwin

1 Incl ERWIN
as

SADEN-FL 1 September 1976

MEMORANDUM THRU: DIRECTOR, SAD Laboratory

FOR: CHIEF, F & M Branch (SADEN-F)

SUBJECT: Trip Report on Procurement of Rock and Soil Samples from Diversion Channel, Richard B. Russell Project

1. Place and Date: Richard B. Russell Project Site, vicinity of Elberton, Georgia on 25 and 26 August 1976.

2. Purpose: Inspect wall rock exposed in the central portion and banks of the diversion channel at Richard B. Russell Project and procure oriented samples condusive to evaluation of movement directions and stress history in the geologic framework of the project area.

3. Attendance: Capt. Mel Lynch, Project Engineer
Mr. Jack Keeton, Savannah District
Mr. Earl Titcomb, Savannah District
Mr. Jim Neiheisel, South Atlantic Division Laboratory

4. Narrative:

a. In recent time, particular attention is being directed to the stress history in foundations of dam structures to assure that active faults are not present and to determine as closely as possible the relative time of movement and orientation of former stresses along inactive stress zones.

b. On the afternoon of 25 August, the writer and Mr. Jack Keeton inspected visible stress zones in the diversion channel exposed by recent excavation. An oriented sample was taken at Station 19 + 40 on the right side of the diversion channel along a surface with a trend N 10° E and dipping 45 degrees west. Several samples were also obtained from Station 21 + 15 (right of centerline) along the landward bank of the diversion channel. These samples were taken across a 5 foot alteration zone and selected portions of adjacent wall rock for composition control analysis.

c. On the morning of 26 August, the writer and Mr. Earl Titcomb inspected the diversion channel stress zone and orientated samples were obtained at Station 17 + 40 (right of centerline) on the upstream side of the diversion channel and at Station 20 + 95 (right of centerline) on the downstream of the diversion channel. The former had an orientation of N 35° E strike and 56° W dip and the latter had an orientation of

N 30° E and 56° West dip. In addition, several jar samples were taken in vicinity of the altered stress zone and adjacent wall rock to access the resulting alteration based on the mineralogy of the rock in the affected zone and adjacent wall rock. An inspection was also made of cores taken during the exploration drilling phase of the project and three samples were obtained between 112.5 and 116.6 feet depth of Core Hole DC-24 which contained evidence of the altered zone.

5. The samples obtained from the Richard B. Russell Project will be analyzed at the South Atlantic Division Laboratory using X-ray diffraction and petrographic techniques to correlate the orientation of microscopic features with field evidence and other investigative reports concerning the stress history of the project area. A separate report of findings will be provided. This work is being funded by the Savannah District in accordance with discussions between the writer, Mr. Erwin (SADEN-FL), and SASEN-FG personnel.

JAMES NEIHEISEL
Geologist

Copy furnished:
Capt. Lynch, Ft. Gordon Res. Engr. Office
Mr. Earl Titcomb, SASEN-FG

U.S. ARMY ENGINEER DIVISION LABORATORY

SOUTH ATLANTIC

STRESS HISTORY IN VICINITY OF

RICHARD B. RUSSELL DAM SITE

CORPS OF ENGINEERS
MARIETTA, GEORGIA
16 December 1976

Reqn. No.
EN-FG-7T-46

Work Order
No. 0184

App 3
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Section D

PREFACE

The Foundations and Materials Branch, U. S. Army Engineer District, Savannah, in Requisition No. EN-FG-7T-46 dated 17 September 1976, to the Director, South Atlantic Division Laboratory (SADEN-FL) requested field observations, petrographic and X-ray diffraction analyses, and potassium-argon dating of rock samples from the diversion channel at Richard B. Russell dam site for the purpose of estimating the stress history at the dam site. Dr. James W. Erwin, SADEN-F, and Messrs. Earl Titcomb and Robert Stansfield, SASEN-FG, provided assistance in field observations and in obtaining oriented field samples. The field sampling, petrographic and X-ray diffraction analyses were performed by Dr. James Neiheisel at SAD Laboratory. Potassium-argon dating of selected samples was performed by Dr. Marion Wampler of the Geophysical Science Laboratory at Georgia Institute of Technology, Atlanta, Georgia. The latter work appears as Appendix A to this report which was prepared by Dr. Neiheisel.

The work was performed under the general direction of Mr. Robert J. Stephenson, Director, South Atlantic Division Laboratory and Mr. Robert L. Crisp, Jr., Chief, Foundation and Materials Branch, South Atlantic Division.

U.S. ARMY ENGINEER DIVISION LABORATORY, SOUTH ATLANTIC CORPS OF ENGINEERS MARIETTA, GEORGIA PETROGRAPHIC REPORT		DISTRICT Savannah PROJECT RICHARD B. RUSSELL DAM CONTRACT NO. ---
SOURCE Richard B. Russell Diversion Channel	LAB NO. 232/885 - 899	DATE REPORTED 16 December 1976
DATE RECEIVED 26 August 1976	REQ. NO. EN-FG-7T-43, EN-FG-7T-46, EN-FG-77-09	WORK ORDER NO. 0169, 0184, and 0233

STRESS HISTORY IN VICINITY OF RICHARD B. RUSSELL DAM SITE

Petrographic and/or X-ray diffraction analyses have been made in accordance with CRD-C 127-67 and/or EM 1110-2-2000. Thin section studies, petrographic oil immersion studies, and megascopic examination have been performed as necessary for evaluation procedures and photomicrographs of thin sections, where applicable, appear as figures in the report. X-ray diffraction techniques, if applicable to this testing, include ethelene glycol and heat treatment of sedimented slides as corroborative diagnostic tests to the powder press technique, and X-ray diffractograms appear as plates. Other tests necessary for this investigation are described in the report.

Detailed petrographic descriptions and pertinent remarks regarding acceptance of individual rock types, soils, or fine aggregate and other earth materials are included in the tables. The summary below presents key data resulting from the testing.

13 Incl
   Figures
12 Plates
   Tables
1 Appendix

SUMMARY

Petrographic, X-ray diffraction, and potassium-argon dating analysis of oriented rock samples from an altered felsic dike trending parallel to a fault and a mafic dike truncated along the fault has provided information enabling interpretation of the stress history at Richard B. Russell dam site. Analysis of microstructures and composition of rock and soil samples was performed at SAD Laboratory and potassium-argon dating accomplished by Dr. J. M. Wampler at the Geophysical Sciences Laboratory at Georgia Tech.

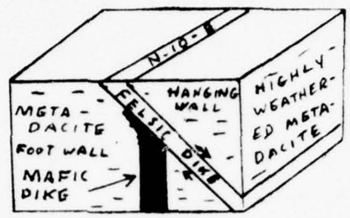
The felsic dike intrusive appears to be structurally controlled along a pre-existing fault zone in the host rock of metadacite. A truncated, older mafic dike, which does not penetrate the felsic dike and which appears to be offset from the opposite, more highly weathered, hanging wall also supports the view that felsic dike was localized along a pre-existing fault zone and that hydrothermal alteration followed this same pathway at a later date. Potassium bearing minerals in the mafic and altered felsic dike subjected to potassium-argon dating provide key information relating to the stress history of the area.

REPORTED BY: ☒ PHONE ☐ WIRE	TESTED BY JN	CHECKED BY RJS
DATE 11 Nov 1976, Neiheisel to Stansfield	SAMPLED BY J. Neiheisel	

PETROGRAPHIC REPORT (cont'd) PROJECT **RICHARD B. RUSSELL DAM, Savannah District**

REQ'N NO. **EN-FG-7T-43, EN-FG-7T-46, EN-FG-77-09** W.O. NO. **0169, 0184, and 0233**

A sketch diagram of the altered felsic dike situated along an older fault zone in the diversion channel at Richard B. Russell dam site is depicted below, and a summary analysis of the stress history based on field observations, potassium-argon dates, and published papers in scientific journals, unpublished M. S. dissertations from universities, and Georgia Geological Society field trip guide book is presented as follows.



Sketch Diagram of Felsic Dike Located Along Fault

Age of Rock Unit or Event	Basis
1. Metadacite 560 - 570 m. y.	Rb - Sr whole rock analysis by Carpenter (1976).
2. *Faulting and multiple deformation of Little River Series.* Mafic dike - 355 $\pm$ 11 m. y. Fault N 10^{o}E - less than 355 m.y.	K-Argon dating of <u>mafic dike</u> at station 23+50 by Wampler (1976). Field observation shows fault younger than mafic dike.
3. Felsic dike emplacement 357 $\pm$ 11 m. y.	K-Argon dating of feldspar from felsic dike at station 17+40 by Wampler (1976).
4. Hydrothermal alteration of felsic dike. 272 $\pm$ 6 m. y.	K-Argon dating of muscovite-sericite from altered felsic dike at station 20+95 by Wampler (1976).
Siloam granite pluton 40 miles to SW is probable source of hydrothermal solutions. 269 $\pm$ 3 m. y.	Rb - Sr whole-rock date of nearest granite pluton at Siloam, Georgia by Jones and Walker (1973).
5. Slight movement along old fault zone as observed in the felsic dike as a post hydrothermal event.	Widespread stress and movement along Triassic faults of the Inner Piedmont.

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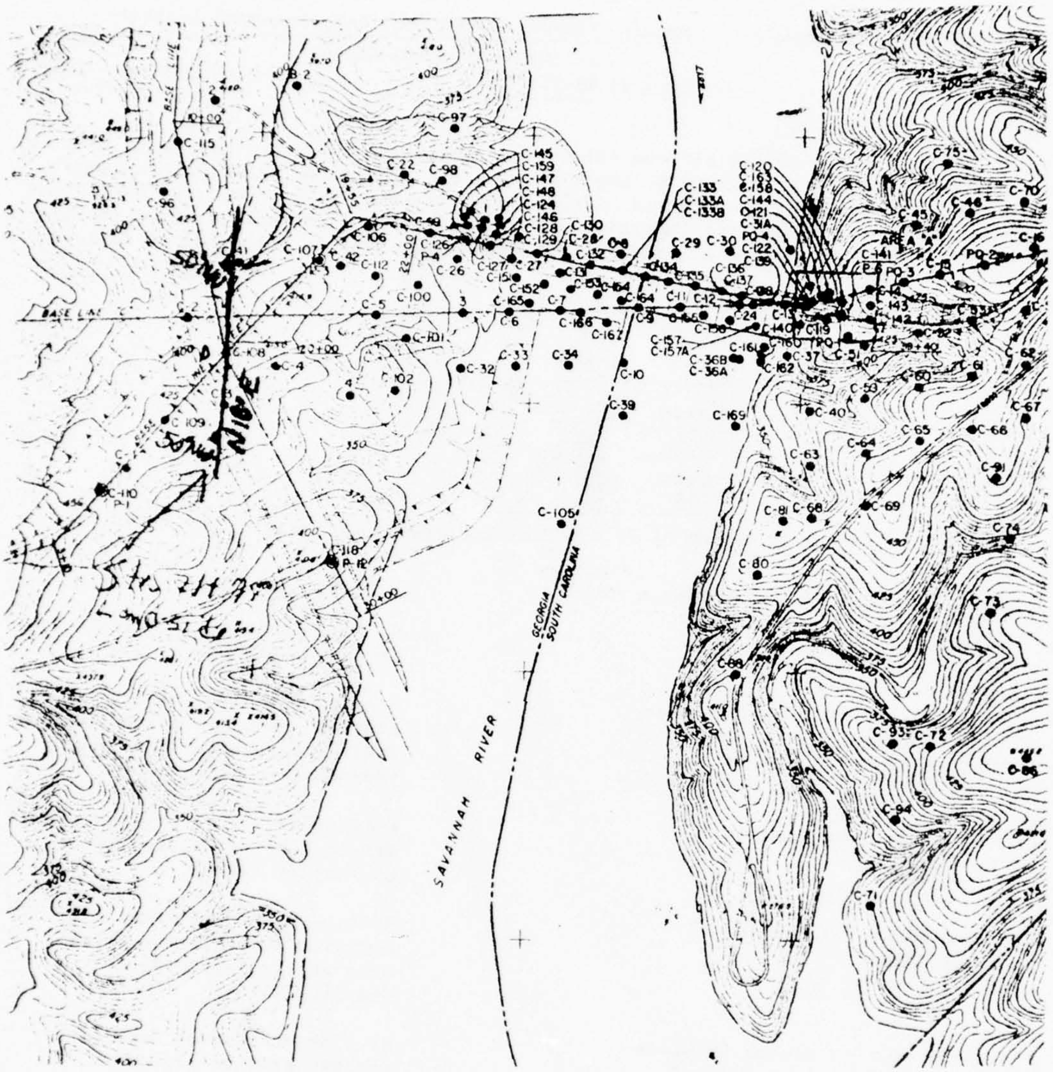

Figure 1. Location of fault zone and altered felsite in diversion channel of Richard B. Russell Project. The fault and alteration zone strikes N 10°E and dips 50°NW. Wall rock alteration appears confined to the fault zone of felsite with most intense alteration to the southwest.

The age of the fault in the diversion channel at Richard B. Russell dam site is considered to be Devonian in age since the fault truncates the 355 $\pm$ 11 million year mafic dike. The felsite implacement must have occurred soon after the faulting and hydrothermal alteration of the dike rock during igneous events of the Permian. Minor stress has occurred since then with maximum concentration at the dam site area along the ancient fault during Triassic time.

Detailed consideration of stress history at the Richard B. Russell dam site is presented in the following paragraphs, tables, appendix, figures, and plates of this report.

DETAILED PETROGRAPHY

Introduction

An exposed ancient fault and altered felsic dike rock cuts across the diversion channel at Richard B. Russell dam site and is exposed in the west bank of the diversion channel. This is one of the many ancient faults known to exist within the Piedmont province framework of the eastern United States. Because of the localization of a felsic dike rock along the ancient fault and the subsequent hydrothermal alteration of the dike rock and the relationship of older mafic dikes to this fault, it is possible with potassium-argon dating to establish the history of the stress events at Richard B.Russell dam site.

The location of the fault across the diversion channel at Richard B. Russell dam site is depicted in Figure 1. The fault trends N 10° E and dips 50° NW and the hanging wall block above the fault zone is more highly weathered than the footwall block. Oriented samples were obtained from four locations along this fault zone and from boring DC 24 (see Figure 2). Petrographic and X-ray diffraction analyses of these samples are presented in Table 1 and potassium-argon dating in Appendix A. The stress history based on this field and laboratory evidence as well as corroborative evidence from published data of adjacent study areas is presented in sequence from the oldest to youngest events in the following paragraphs.

Metadacite Country Rock

The country rock or oldest rock unit at the diversion cheannel is metadacite as disclosed by petrographic analysis of rock from core hole boring DC-24 (see Figure 2 and Table 1). This is similar to the Lincolnton Metadacite described by Paris (1976) for the area to the southwest as "typically a quartz porphyry, consisting of large phenocrysts of blue, opalescent quartz in a fine matrix of quartz and feldspar". A geochronological study of the Lincolnton Metadacite by Carpenter (1976) based on Rb - Sr whole rock analyses and U-Pb analyses of zircon have been completed, and both provide ages between 560 - 570 million years or Cambrian in age.

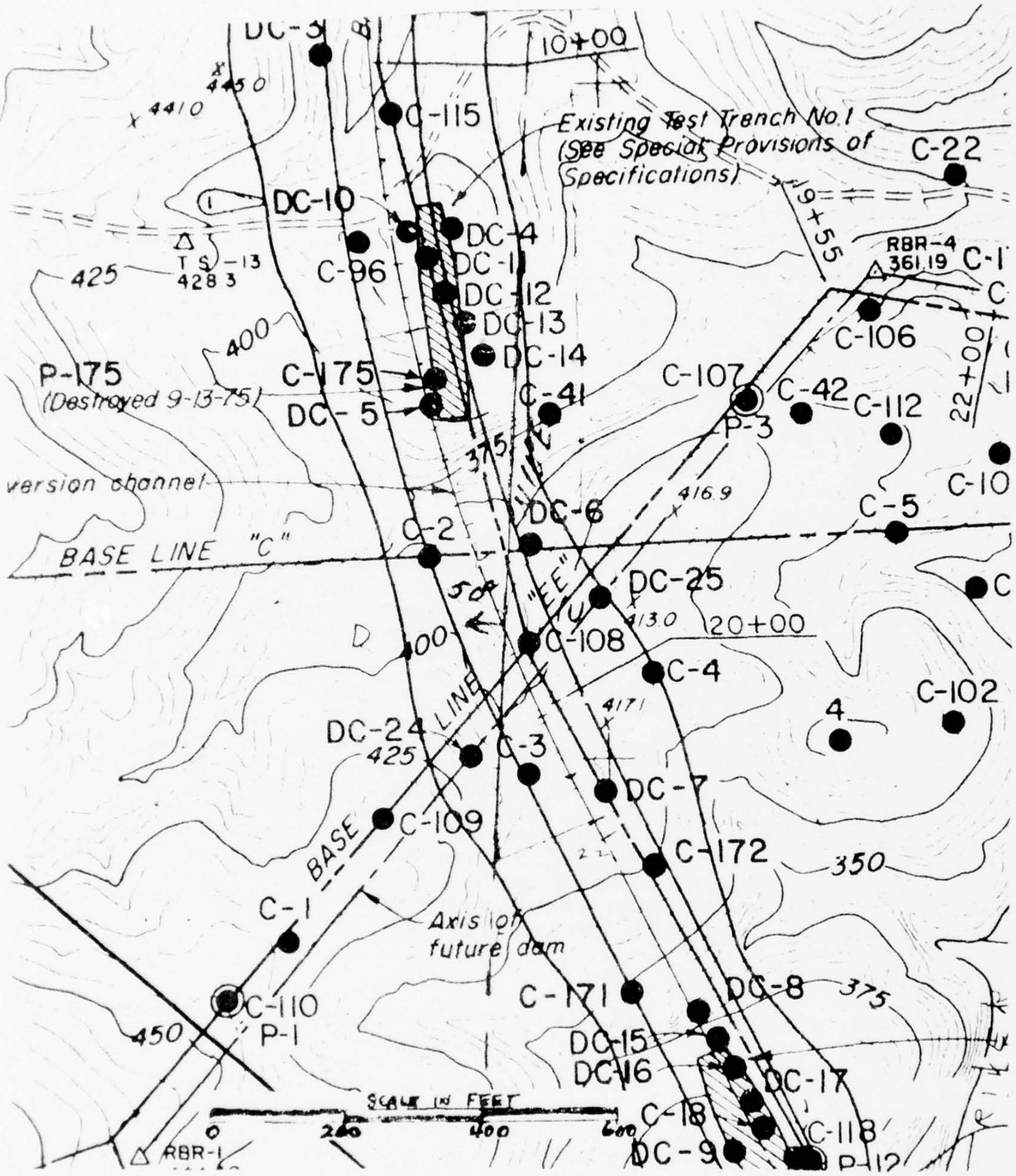

Figure 2. Location of core hole DC-24 in relation to fault along diversion channel.

TABLE 1. Classification of material, mineral composition, and texture description and remarks regarding petrographic testing.

Lab and/or Field No.	Classification of Material	Percent Mineral Composition	Description and Remarks
232/885 17+40 (R)	Altered Felsite (Pink Zone)	95 Feldspar 5 Sericite	Least altered, pink feldspar band in central portion of altered felsite zone. Oriented sample.
232/886 17+40 (R)	Altered Felsite (Grey, lineated zone)	50 Sericite 45 Feldspar 5 Other (Magnetite, etc.)	Grey, lineated altered feldspar band. Magnetite trains are lineated parallel to dip surface. Magnetite up to 5 mm size.
232/887 17+40 (R)	Altered Felsite (Plastic Layer)	60 Sericite 40 Feldspar Tr.Magnetite	White, fine grained, plastic band on east side of altered felstie zone.
232/888 17+40 (R)	Soil Profile(East) (Metadacite)	40 Montmorillonite 10 Chlorite 35 Quartz 15 Feldspar	Brown soil sample from 2 ft. east of altered felsite zone.
232/889 17+40 (R)	Soil Profile(West) (Metadacite)	40 Montmorillonite 25 Quartz 25 Feldspar 5 Sericite 5 Other	Brown soil sample from 1 ft. west of altered felsite zone.
232/890 19+40 (R)	Altered Felsite	60 Sericite 40 Feldspar Tr.Magnetite	Oriented sample from central portion of altered felsite zone
232/891 19+40 (R)	Altered Felsite	70 Sericite 30 Feldspar Tr.Other	White powdery sample parallel to pressure surface.

Project Richard B. Russell Project Req'n No. EN-FG-7T-43 W.O. NO. 0169

Sheet 1 of 3

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TABLE 1. Classification of material, mineral composition, and texture description and remarks regarding petrographic testing.

Lab and/or Field No.	Classification of Material	Percent Mineral Composition	Description and Remarks
232/892 20+95 (R)	Altered Felsite	30 Sericite 65 Feldspar 5 Magnetite Tr. Other	Least altered portion of oriented rock sample from altered felsite zone.
232/893 20+95 (R)	Altered Felsite	82 Sericite 15 Feldspar 3 Kaolinite	White, fine grained, altered fault gouge.
232/894 20+95 (R)	Soil Profile(West) (Metadacite)	15 Chlorite 20 Sericite 35 Feldspar 25 Quartz 5 *Kaolinite*	Soil profile of hanging wall 2 ft. from altered felsite zone. Quartz constitutes the largest particles. Mottled greenish grey and tan color. Highly weathered.
232/895 20+95 (R)	Soil Profile(East) (Diabase)	40 Chlorite 20 Sericite 40 Feldspar	Soil profile of foot wall. Brown color and highly weathered. Possibly soil developed from diabase. Other samples in vicinity contain quartz and appear to be weathered metadacite.
232/896 21+15 (R)	Mafic Dike Rock (Hornblende-chlorite Schist)	20 Feldspar 40 Chlorite 30 Hornblende 7 Sericite 3 Other	Greenish grey, fine grained, foliated, altered dike rock truncated by hanging wall.
232/897 Core DC24 114 ft.depth	Altered Felsite	43 Sericite 54 Feldspar 3 Magnetite	Light grey, fine grained, altered felsite with linear, discontinuous, dark bands of magnetite.

Project Richard B. Russell Project Req'n No. EN-FG-7T-43 W.O. NO. 0169

Sheet 2 of 1

SAD FORM 1417-B
7 MAY 73

TABLE ___. Classification of material, mineral composition, and texture description and remarks regarding petrographic testing.

Lab and/or Field No.	Classification of Material	Percent Mineral Composition	Description and Remarks
232/898 Core DC-24 116 ft.depth	Metadacite	60 Feldspar 20 Quartz 20 Sericite	Grey, fine to medium grained, partly altered, porphyritic, metadacite. Quartz forms porphyritic texture.
323/899 Core DC-24 112 ft.depth	Metadacite	67 Feldspar 30 Quartz 3 Other	Grey, fine to medium grained metadacite. Feldspars display albite twinning. Less altered than 232/898.

Project Richard B. Russell Project Req'n No. EN-FG-7T-43 W.O. NO. 0169

SAD FORM 1417-B
7 MAY 73

Faulting

The N 10° E trending fault zone is older than the altered felsite that it contains but younger than the country rock in which it occurs. The mafic dikes, truncated by the fault, are also older than the fault. The potassium-argon dating of an unaltered mafic dike from field location station 23+50 reveals an age of 355 $\pm$ 11 million years (see Appendix A). The mafic dike rock from field location station 21+15 contains alteration products (sericite, etc.) and the potassium-argon date of this sample is therefore not considered valid because of this contamination. The fault is younger than the 355 $\pm$ 11 million year mafic dike but older than the altered felsic dike rock which parallels the fault fracture.

The faulting post dates the regional metamorphism of the region which Fullagar (1971) postulates as a Siluvian-Devonian event (420 - 380 million years ago). Paris (1976) cites structural features as evidence that the faulting is a post metamorphic event. Thus, the age relation of the fault correlates with the investigations of Paris (1976) and is fixed more rigidly in absolute time by potassium-argon dating of this investigation as being younger than 355 $\pm$ 11 million years and older than 272 $\pm$ 6 million years; the latter limiting age is based on potassium-argon dating of the hydrothermal alteration which is described in a later section of this report.

Felsic Dike

The felsic dike strikes N 10° E, parallel to the fault zone, and has a variable thickness ranging between 4 to 10 feet. The felsite is hydrothermally altered but relatively fresh unaltered feldspar exists near the central zone. The feldspar from station location 17+40 is least altered and has a fresh appearance (see Table 1); potassium-argon dating indicates an age of 357 $\pm$ 11 million years (see Appendix A and Table 1). This is generally similar to the lower limiting age of the fault if one takes into consideration the 11 million year analytical margin for error in the age determination. Thus, the felsite of generally similar age was probably emplaced very soon after the faulting occurred.

Hydrothermal Alteration

Hydrothermal alteration is apparent throughout the felsite dike with sericite the chief alteration product (see Table 1 and Figures 3 thru 8). The feldspar-rich felsite dike was largely altered to potassium-rich sericite which provides rather ideal material for potassium-argon dating. Much of the potassium was probably introduced with the hydrothermal solutions originating from a siliceous magma. The potassium-argon age determined on a pure sericite fraction from station 20+95 is 272 $\pm$ 6 million years (see Appendix A). This correlates well with the radiometric age of the nearest granitic pluton and the similarity of the hydrothermal alteration at the Magruder Mine (Peyton and Cofer, 1950), situated approximately 12 miles to the southwest of the dam site. Jones and Walker (1973) employing rubidium-strontium, whole-rock dating of the Siloam granite obtained an absolute age of 269 $\pm$ 3 million years. Thus the hydrothermal alteration of the felsite and the emplacement of the

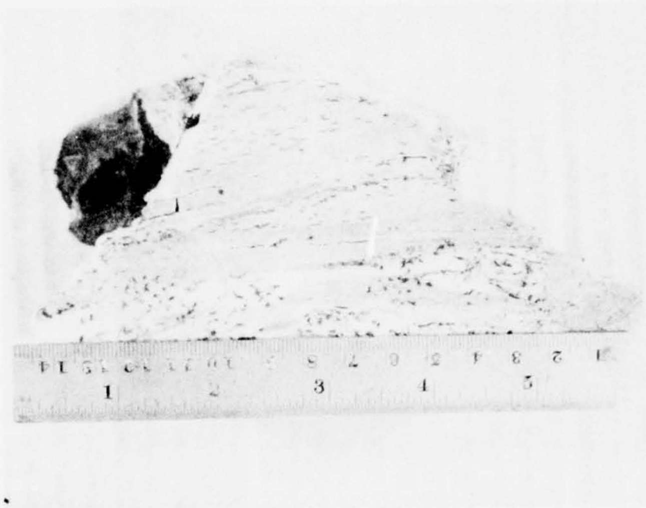

Figure 3. Altered felsite dike rock from station 17+40 (right of diversion channel centerline) showing linear trains of black magnetite. Grey areas are sericite rich and light areas are relatively unaltered feldspar.

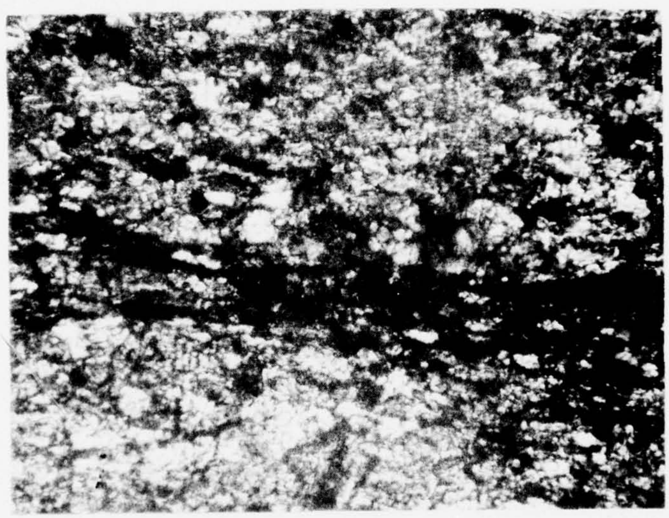

Figure 4. Photomicrograph (100X, Crossed Nicols) of thin section from grey zone of the altered felsite shown in Figure 3. Dark lineations of fine grained magnetite and iron stained areas shown in the center of the photograph trend parallel to major stress surfaces in the altered felsite.

Figure 5. View of central portion of excavation in the diversion channel looking toward the Savannah River showing the smooth, slick pressure faces trending in the dip direction of the fault zone. Apex of the talus cone (left) is at station 18+50. The white, altered felsite zone appearing on the cliff face strikes N 10° E and dips 45° NW.

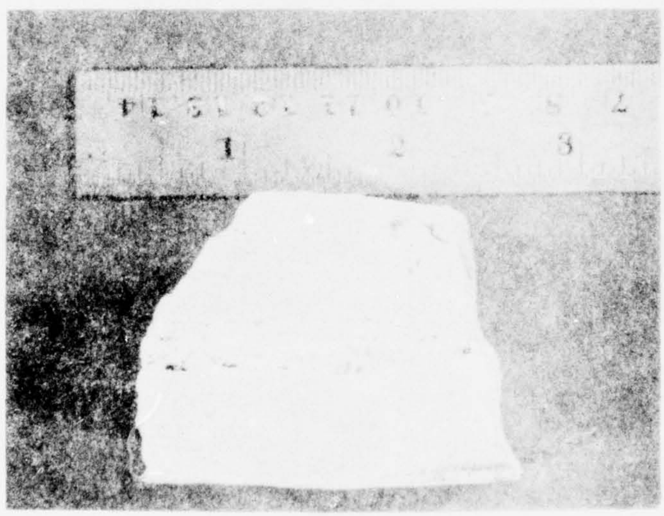

Figure 6. Oriented altered felsite from station 19+40 (right side of centerline). The ruler is on the pressure face and the sliced rock face reveals the linear features which parallel the pressure face in the direction of dip along the fault zone.

Siloam pluton appear to coincide in time if the analytical error inherent in the methods are taken into consideration. The analytical error of the methods could be as much as ± 6 million years for the sericite of the altered felsite dike and ± 3 million years for the Siloam pluton.

Post Hydrothermal Stress

Post hydrothermal stress is observed along the central portion of the felsite dike in the diversion channel as smooth, slick pressure faces (see Figure 5). Lineations in the altered felsite are also observed megascopically and microscopically (see Figures 3 and 6) with alignment parallel to the general 45° NW dip direction of the fault. Although slickensides are not observed in the felsite, the smooth pressure faces and alignment of trains of magnetite suggest that some movement has occurred parallel to the fault since the period of hydrothermal alteration. Fullagar (1971) and others have shown that final major tectonic events which had a major effect on the Piedmont area probably took place during the Triassic period. Bollinger (1973) has demonstrated that strain due to crustual uplift is concentrated along old fault structures and such stress in the vicinity of the dam site would have been along this old Paleozoic fault. The amount of stress in the region of the dam site since the post hydrothermal phase of stress events may be concluded as very minor since the felsite, relatively inert to weathering and physically less competent than fresh country rock (metadacite), reflects little stress and negligible evidence of movement. The wall rock is highly weathered (see Figure 9) while the felsite preserves the graphic details of earth stress in vicinity of maximum stress since the hydrothermal event 279 ± 6 million years ago.

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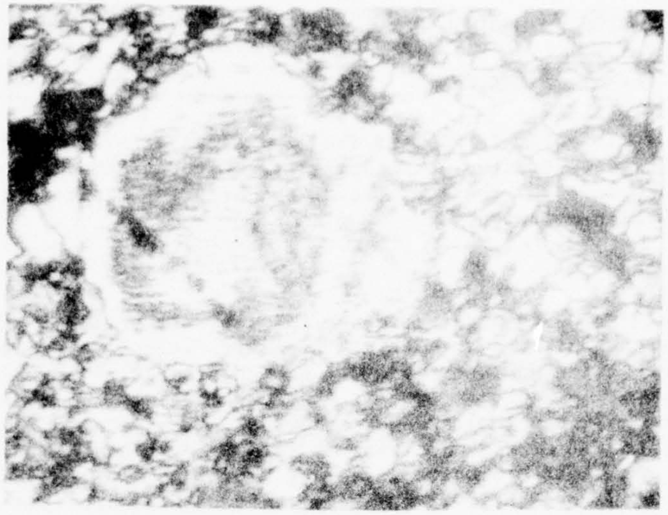

Figure 7. Photomicrograph (100X, Crossed Nicols) of thin section of altered feldspar phenocrysts from central layer of rock specimen shown in Figure 6. The feldspar shows incipient sericitization along cleavage surfaces.

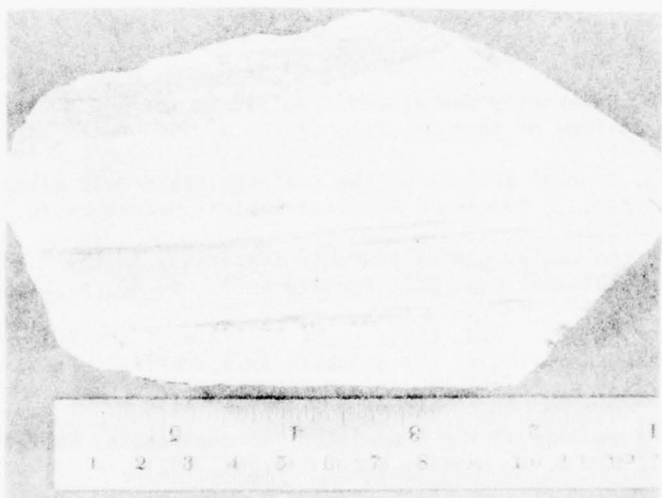

Figure 8. Altered felsite from station 20+95 (right of centerline of diversion channel). The foliation tends to parallel the strike of the alteration zone and dip in the direction of the fault zone.

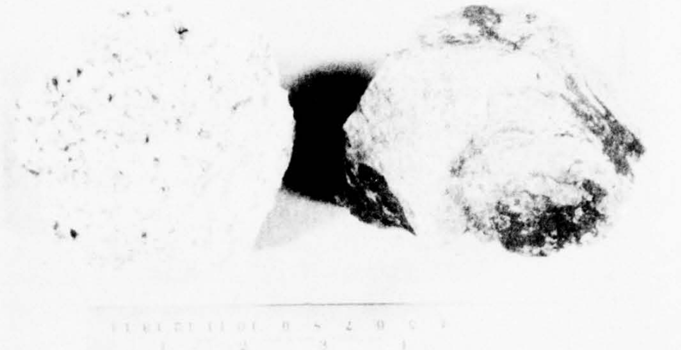

Figure 9. Typical wall rock from footwall in vicinity of fault zone on west side of diversion channel at Richard B. Russell Project. The dark green rock occurs as dikes typically 3 ft. wide truncated by the hanging wall. The lighter colored saprolite appears to be weathered porphyritic metadacite in which quartz grains up to 2 mm size constitute the largest particles.

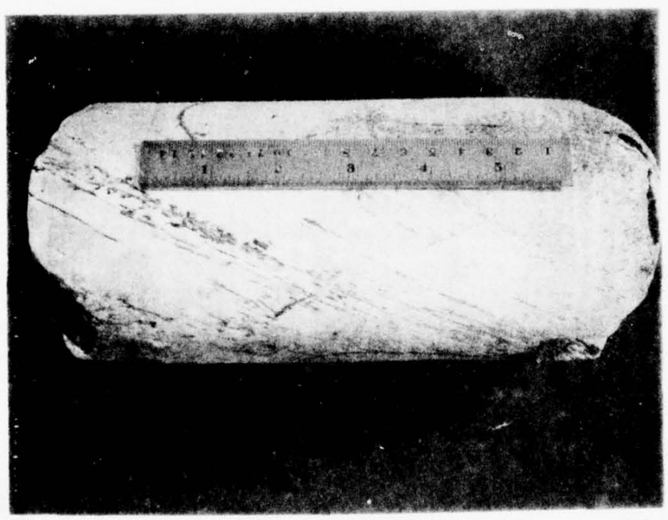

Figure 10. Altered felsite from between 114.0 and 114.8 ft. depth of core hole DC-24. Dark trains of magnetite are the lineated features in this altered felsite.

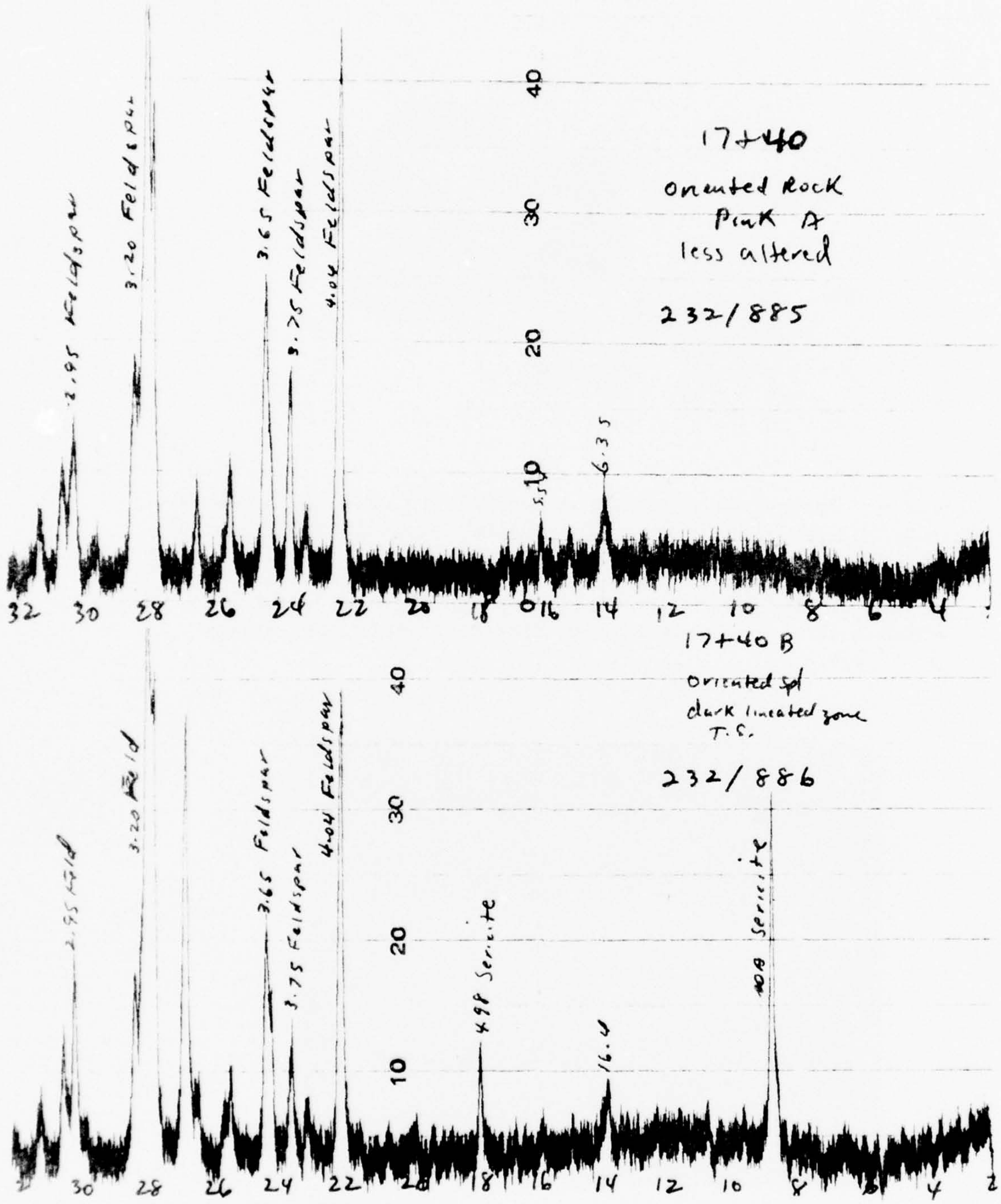

Plate 1. X-ray diffractograms of powder press samples from oriented altered rock from more central altered zone at station 17+40 (right of centerline) in diversion channel, Richard B. Russell project. (SAD Lab Nos. 232/885 & 232/886).

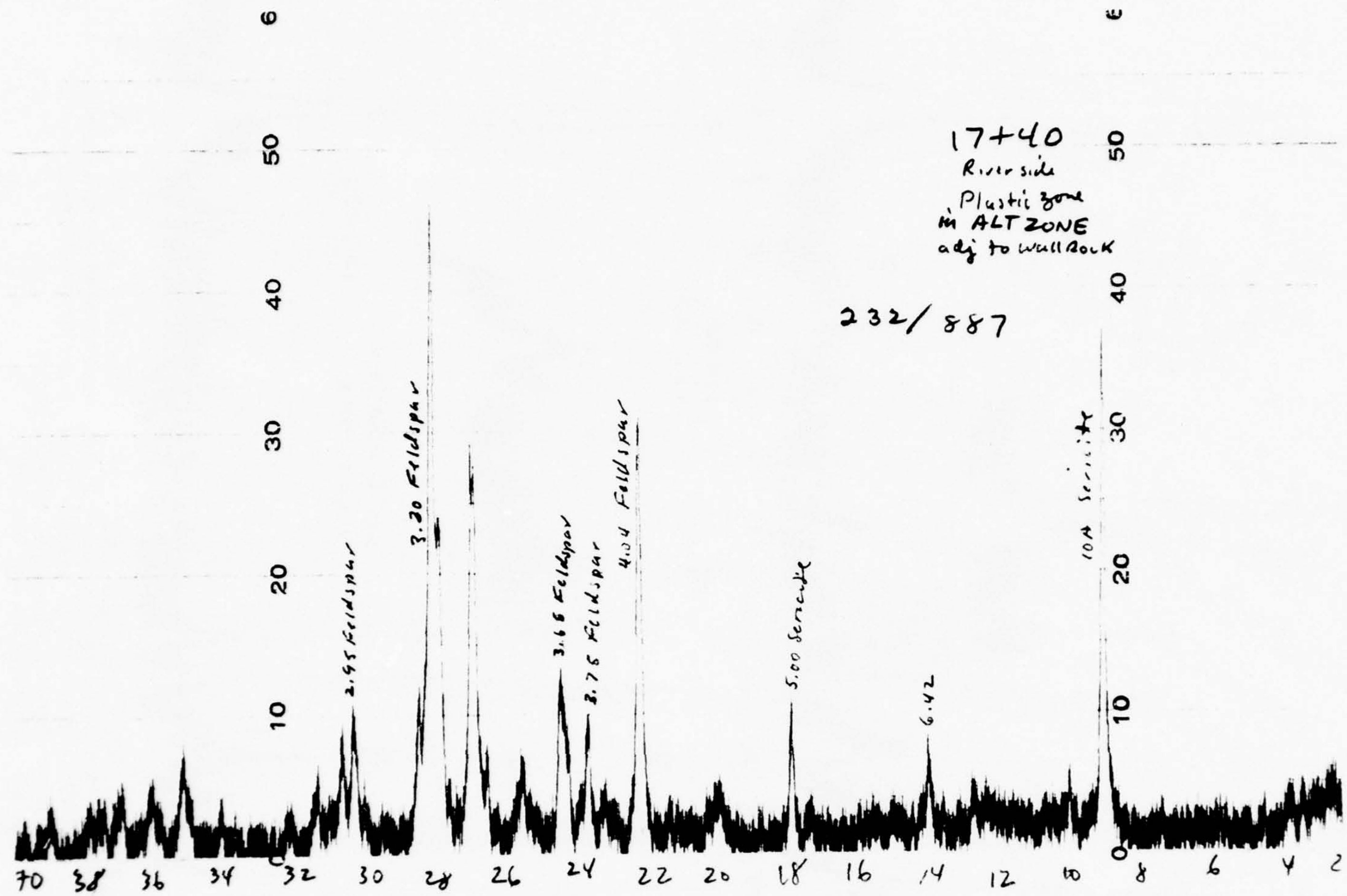

Plate 2. X-ray diffractogram of powder press sample of white, plastic material in altered zone at station 17+40 (right of centerline) in diversion channel, Richard B. Russell Project. (SAD Lab. No. 232/887).

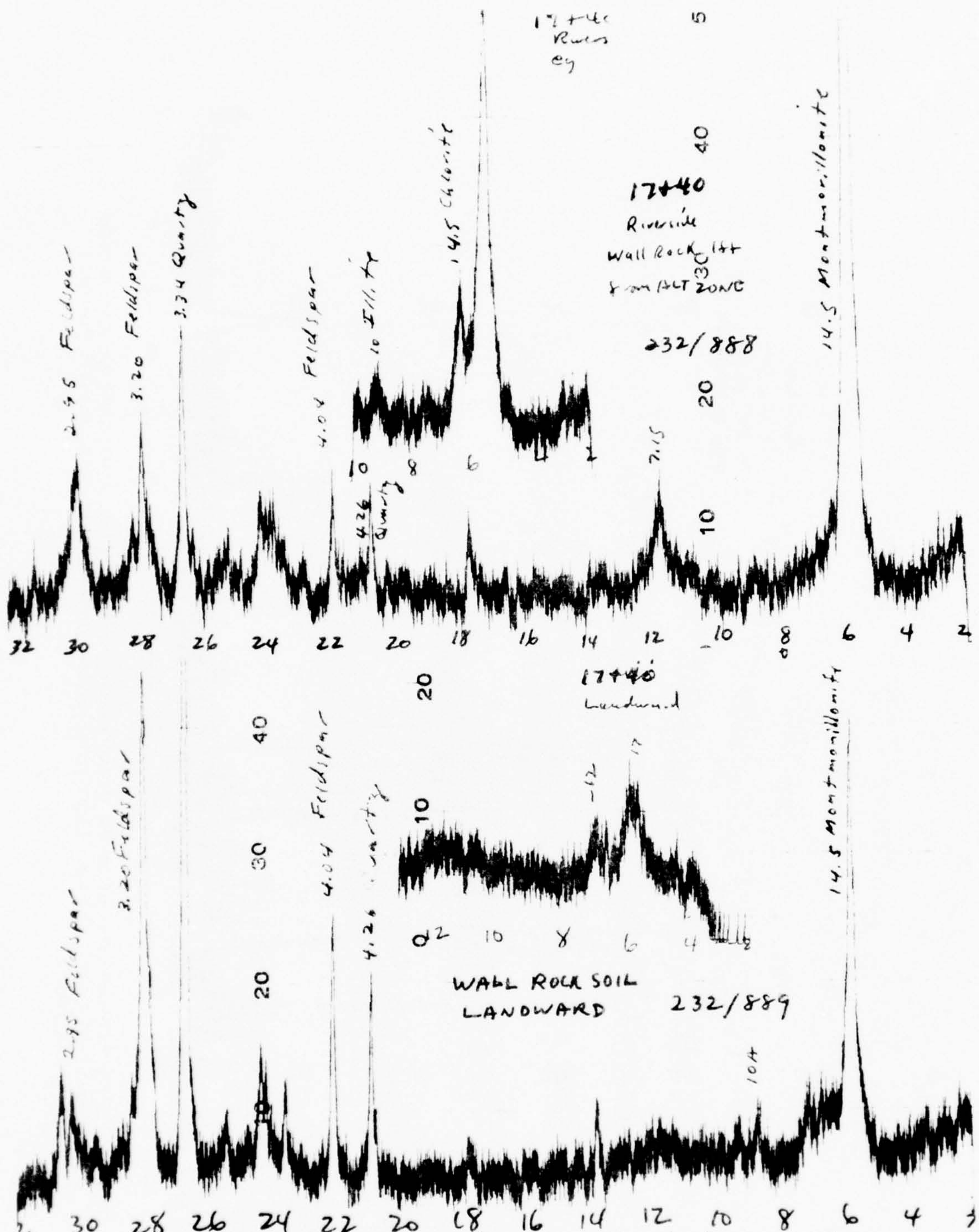

Plate 3. X-ray diffractograms of soil in wall rock adjacent to the altered felsite zone at station 17+40 (right of centerline) in diversion channel, Richard B. Russell Project. (SAD Lab. Nos. 232/888 and 232/889).

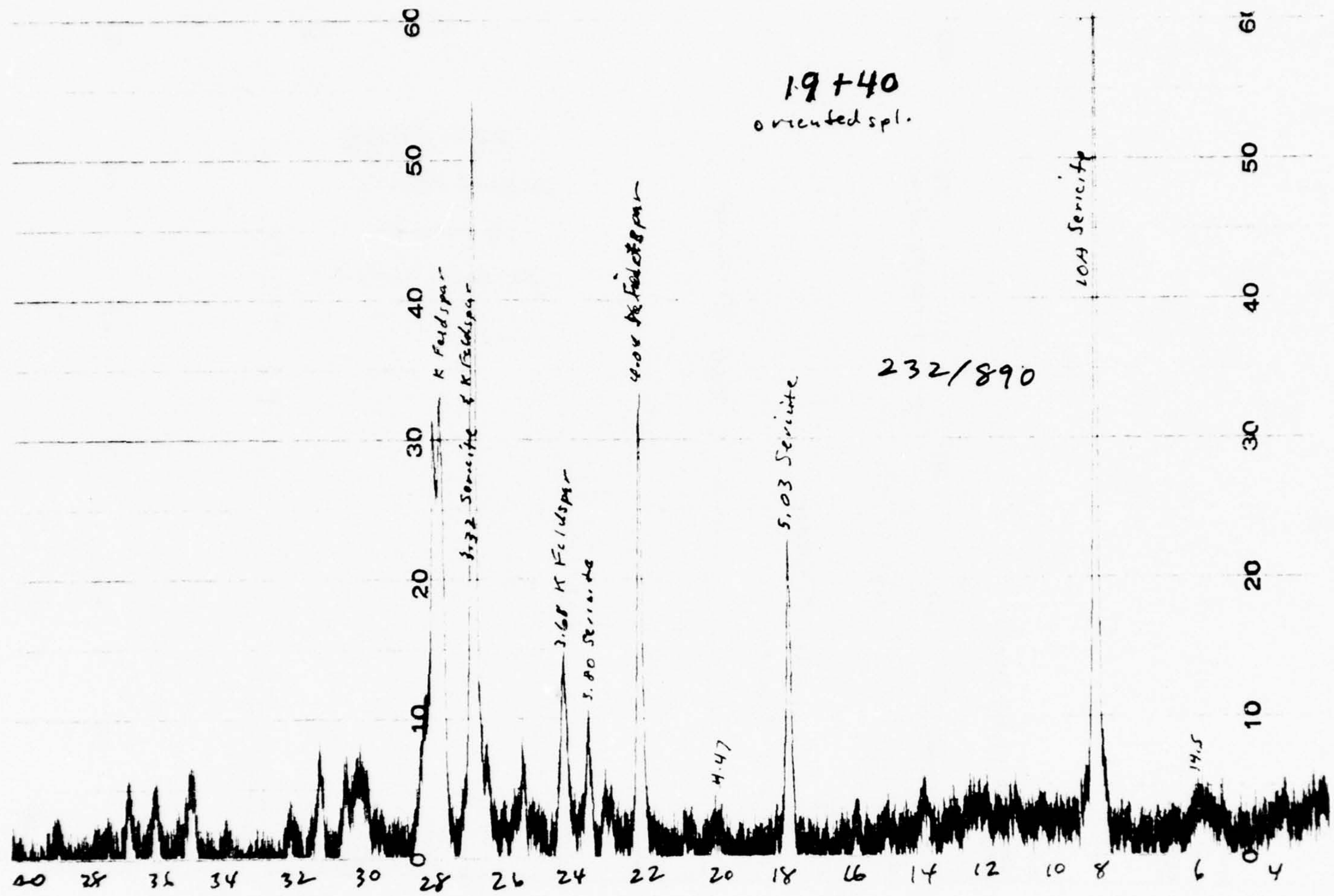

Plate 4. X-ray diffractogram of powder press sample of oriented altered felsite from central portion of alteration zone at station 19+40 (right of centerline) in diversion channel at Richard B. Russell project. (SAD Lab. No. 232/890)

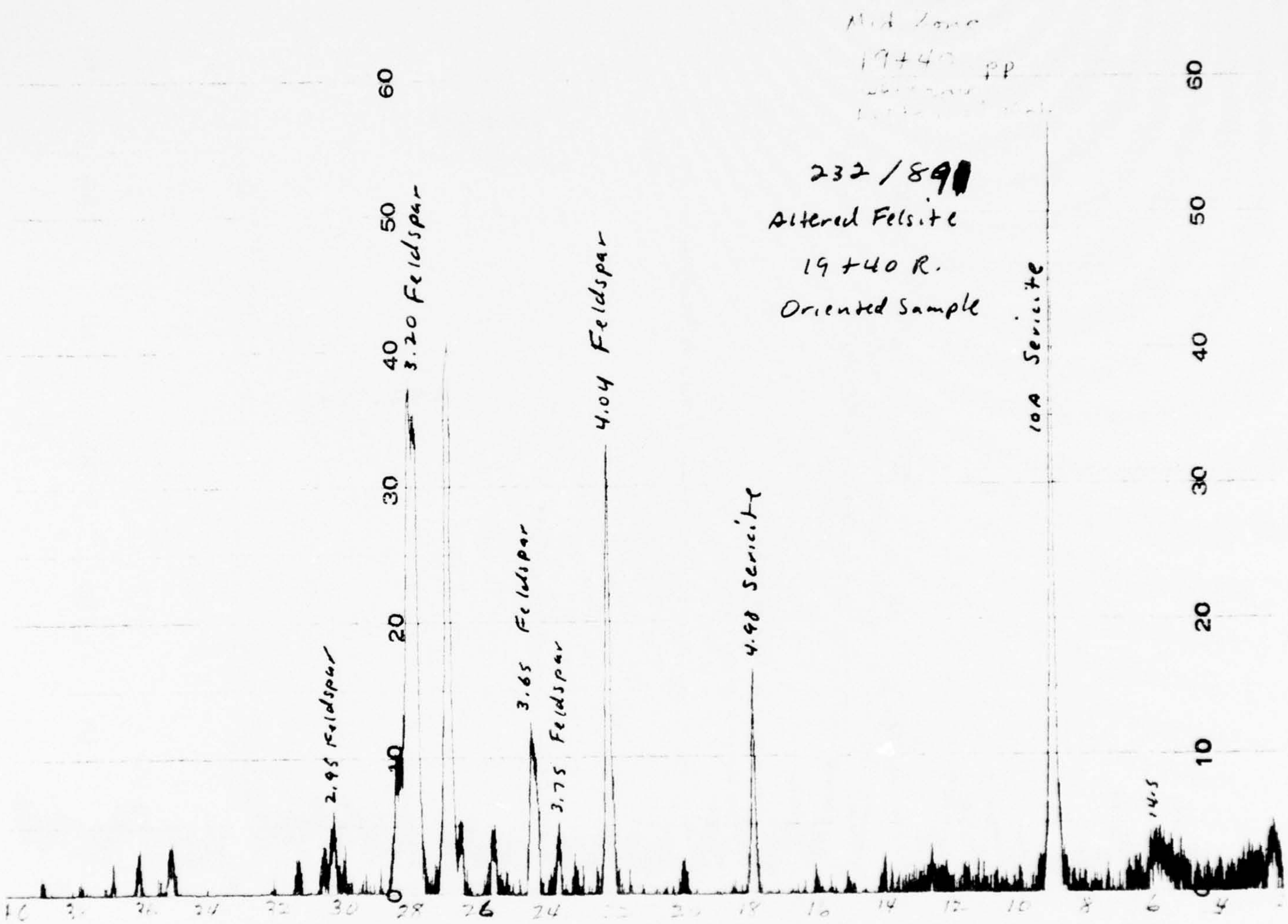

Plate 5. X-ray diffractogram of powder press sample of altered felsite from the more central zone at station 19+40 (right of centerline) in diversion channel of Richard B. Russell project. (SAD Lab. No. 232/891)

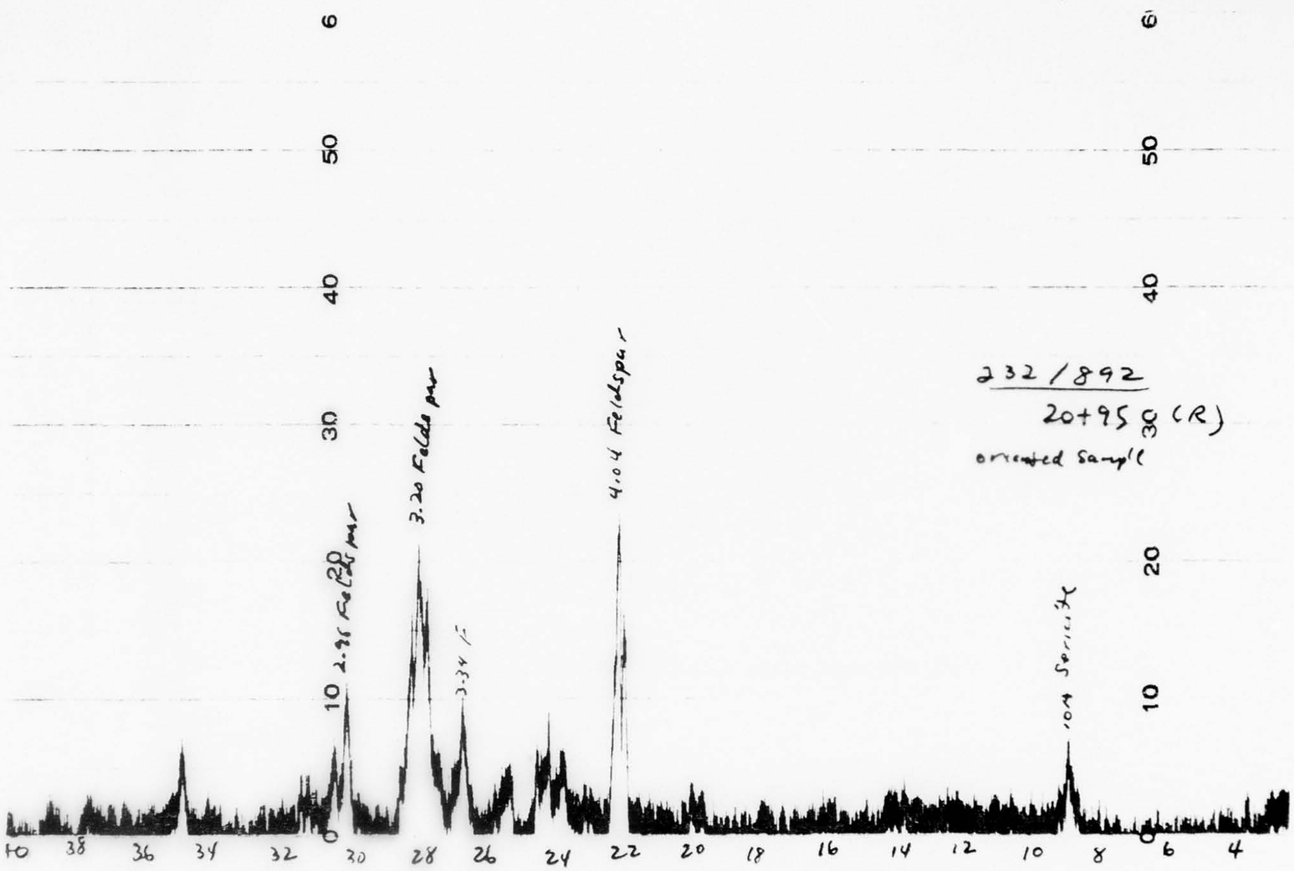

Plate 6. X-ray diffractogram of powder press sample of altered felsite from oriented sample location at station 20+95 (right of centerline) in diversion channel of Richard B. Russell project. (SAD Lab. No. 232/892)

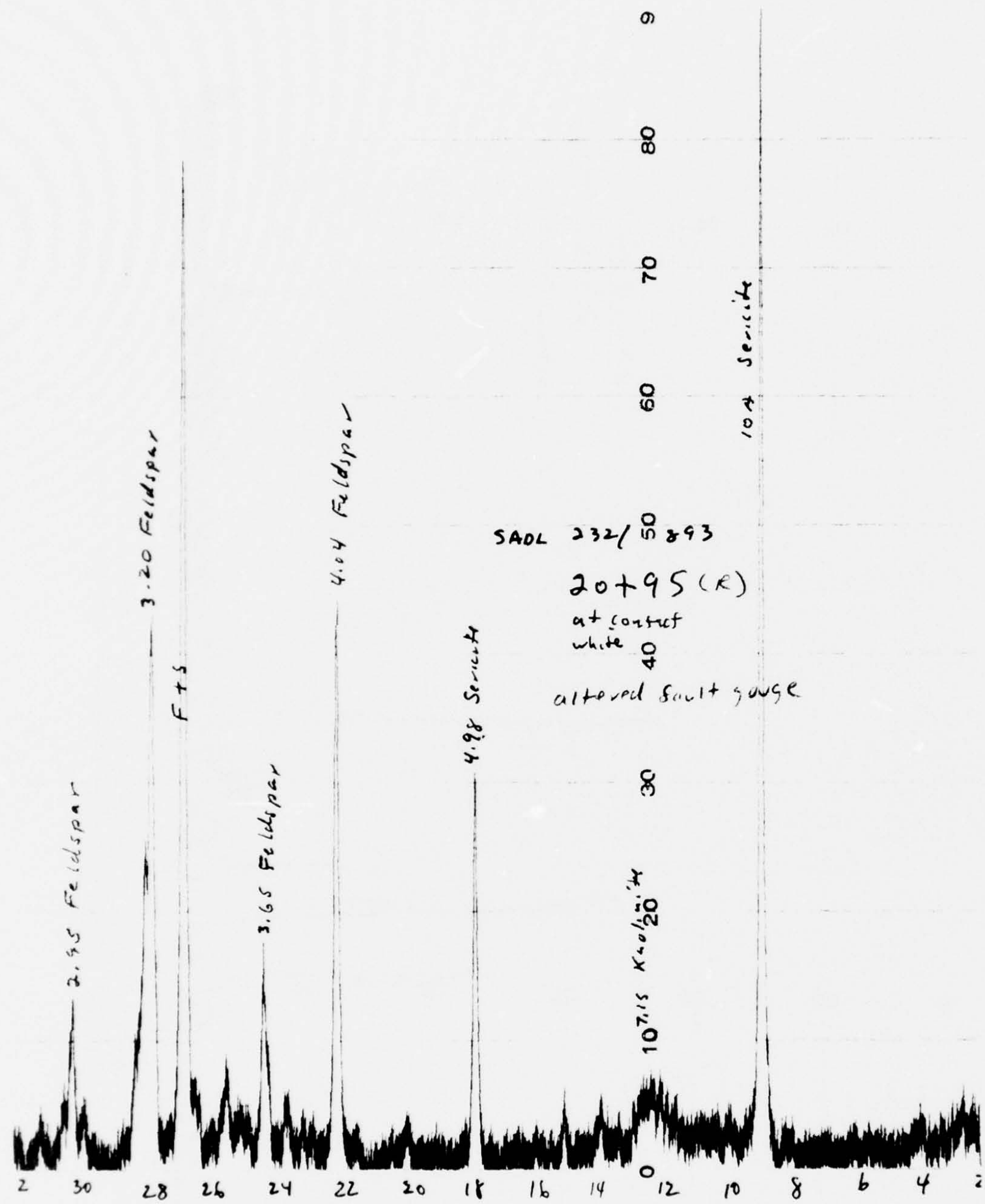

Plate 7. X-ray diffractogram of powder press sample of fine grained powdery material from sericitized fault zone at station 20+95 (right of centerline) in diversion channel west wall at Richard B. Russell project. (SAD Lab. No. 232/893)

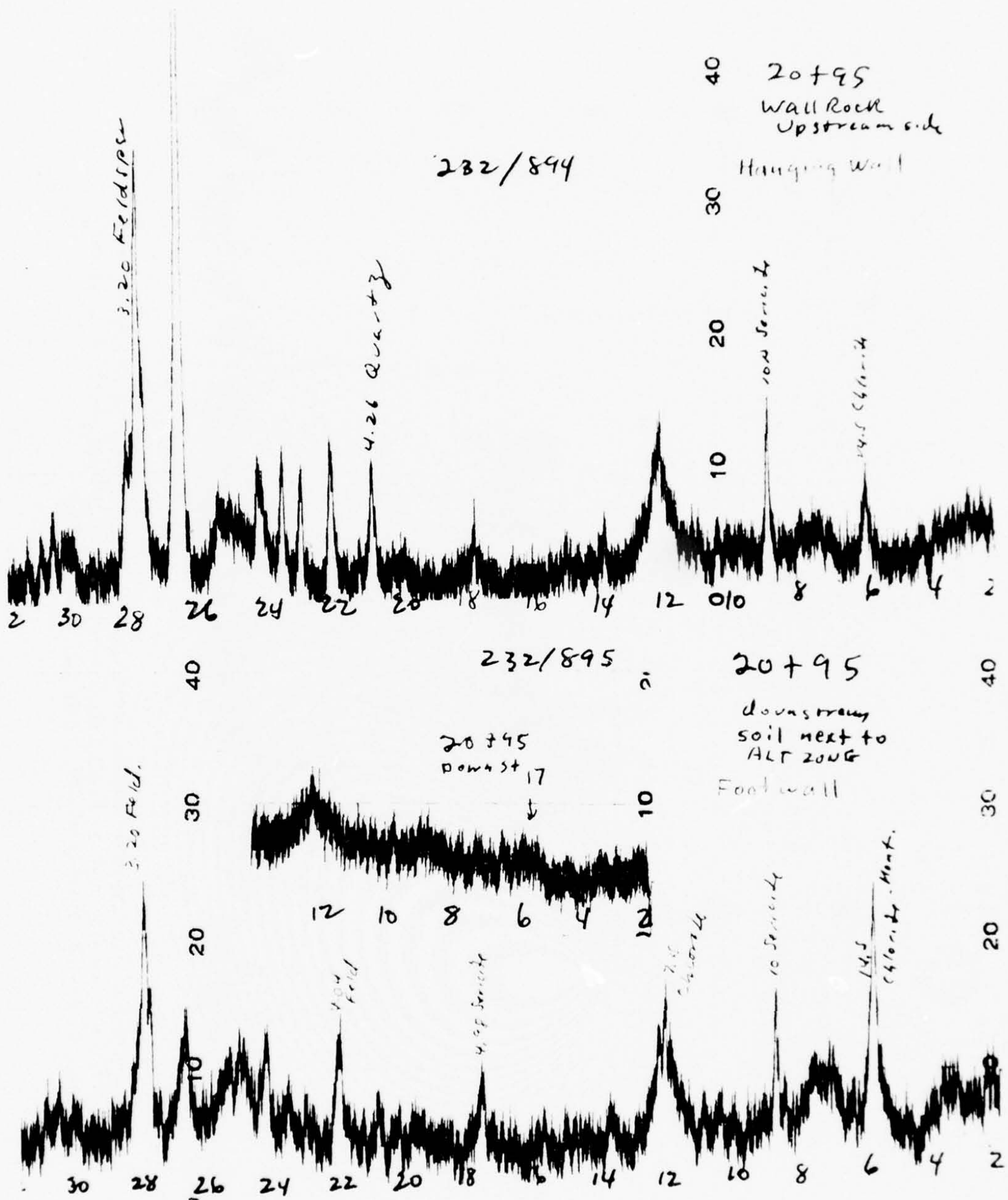

Plate 8. X-ray diffractograms of powder press samples of soil adjacent to altered felsite zone at station 20+95 (right of centerline) in west bank of diversion channel at Richard B. Russell project. (SAD Lab. No. 232/894 and 232/895)

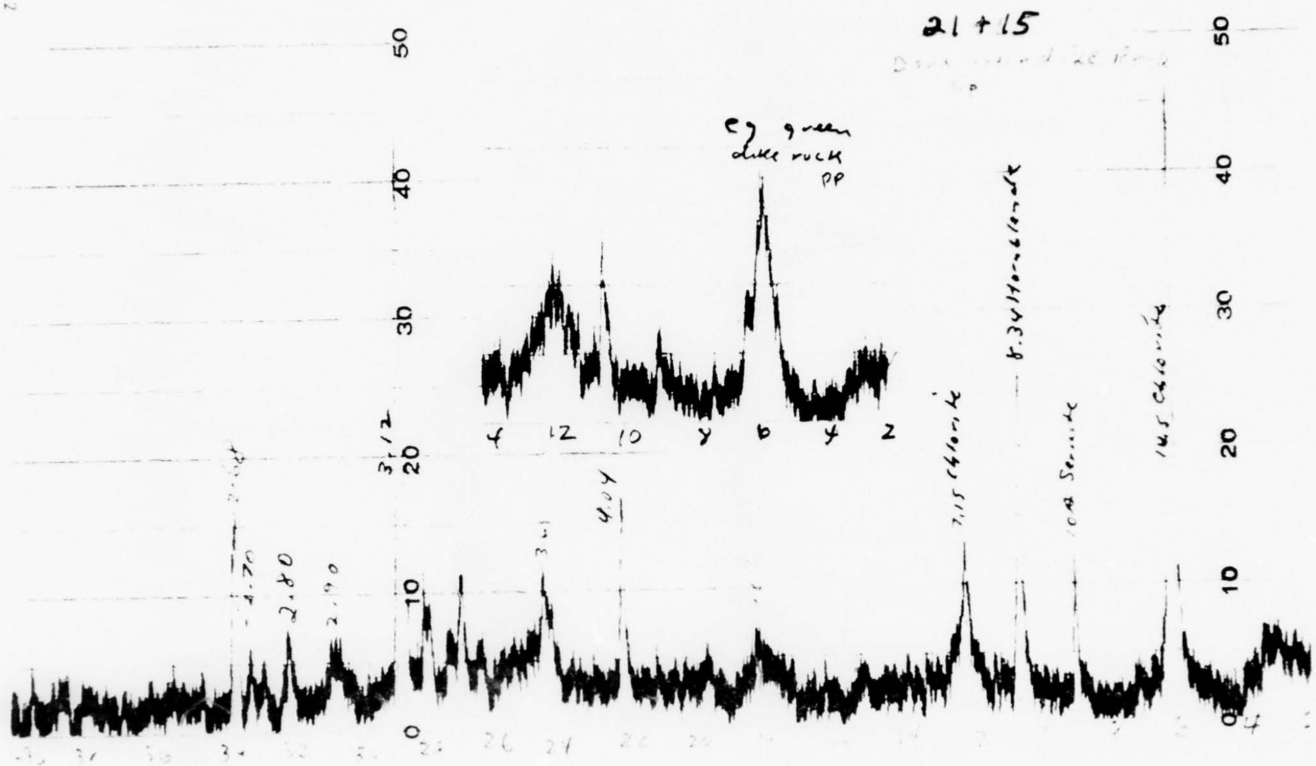

Plate 9. X-ray diffractogram of powder press sample of green dike rock truncated by hanging wall of fault zone at station 21+15 (right of centerline) in west wall of diversion channel, Richard B. Russell project. (SAD Lab. No. 232/896)

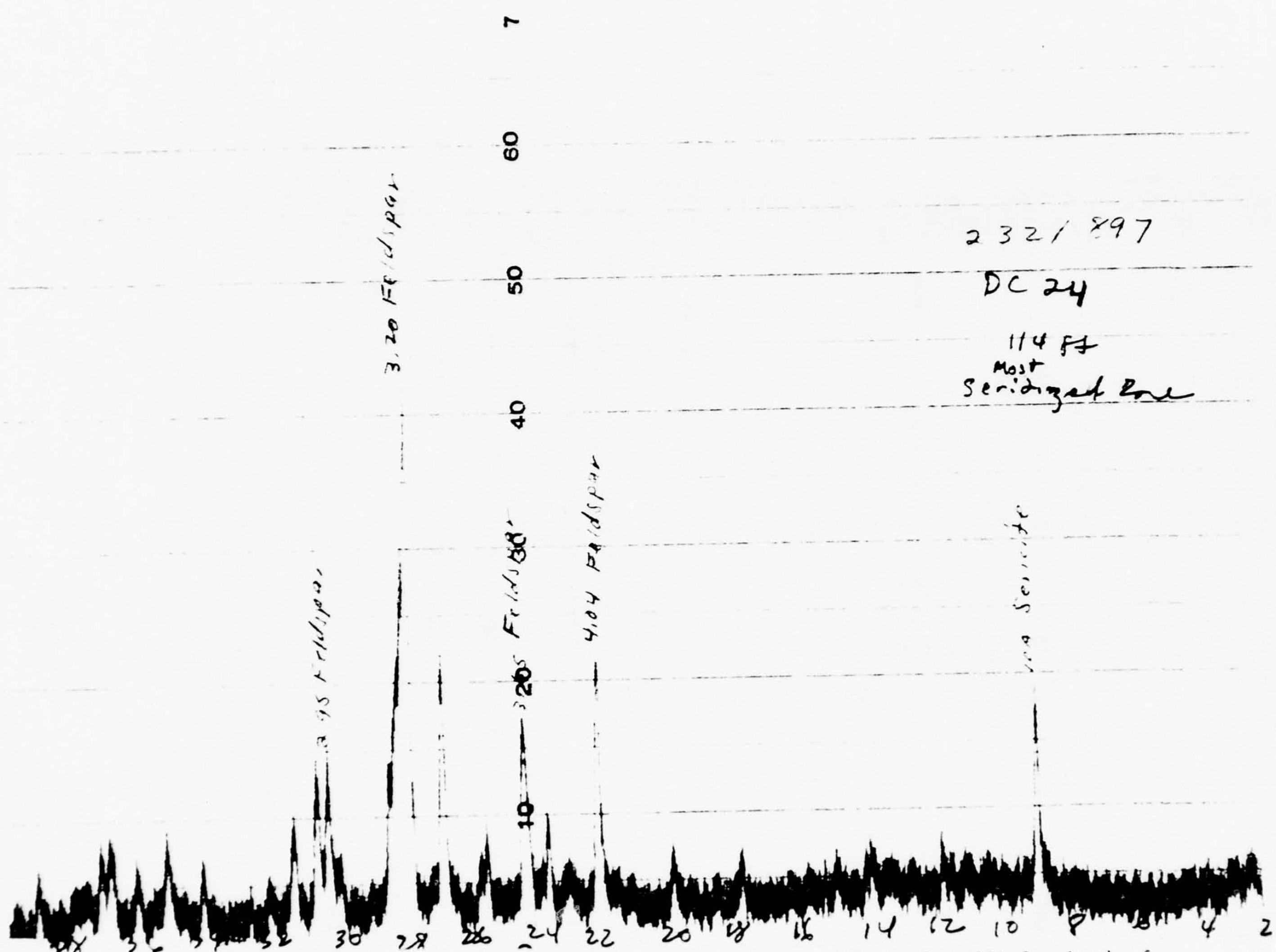

Plate 10. X-ray diffractogram of powder press sample of altered felsite from 114 ft. depth of core DC-24 from Richard B. Russell project. (SAD Lab. No. 232/897)

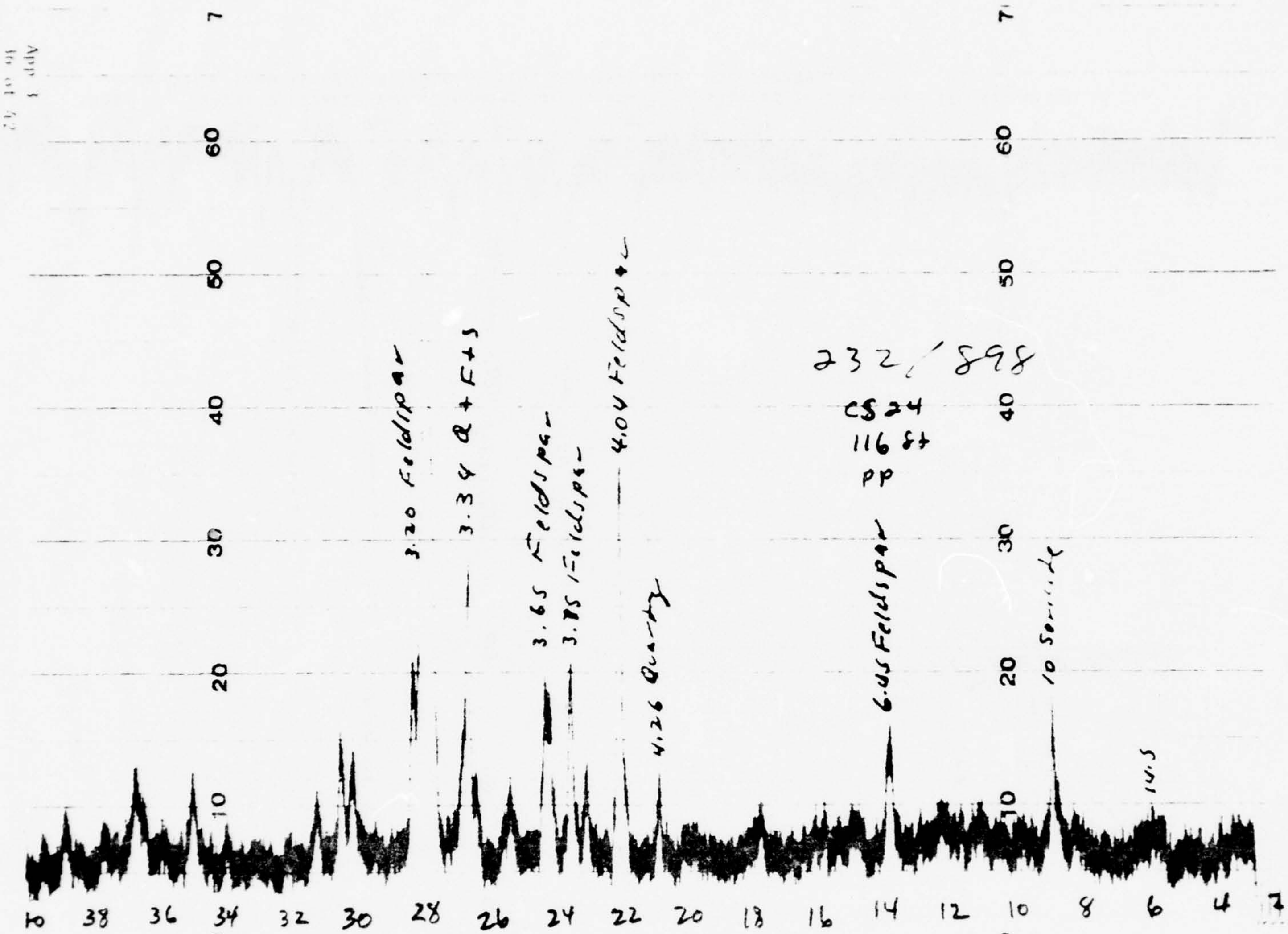

Plate 11. X-ray diffractogram of powder press sample of metadacite from 116 ft. depth of core hole CS-24 at Richard B. Russell dam site. (SAD Lab. No. 232/898)

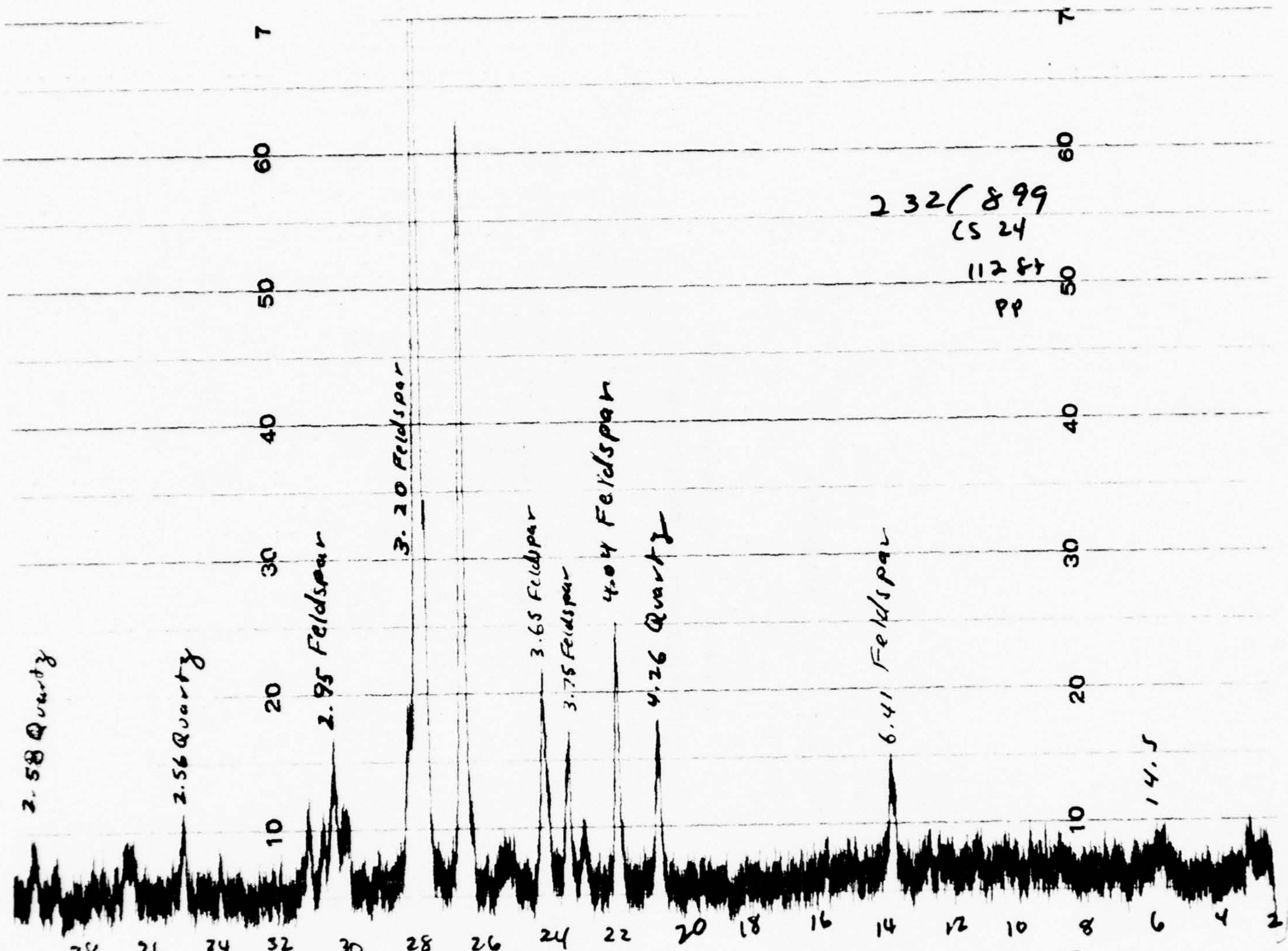

Plate 12. X-ray diffractogram of powder press sample of metadacite from 112 ft. depth of core hole CS-24 at Richard B. Russell dam site. (SAD Lab. No. 232/899)

APPENDIX A

Potassium - Argon Study of Rocks
from Richard B. Russell Dam Site

1 December 1976

GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF GEOPHYSICAL SCIENCES

Atlanta, Georgia 30332
(404) 894 2857

November 23, 1976

Dr. James Neiheisel
South Atlantic Division Laboratory
U.S. Army Corps of Engineers
611 South Cobb Drive
Marietta, Georgia 30060

Dear Jim:

After much delay, I am enclosing the final report on the Potassium-Argon Study of Rocks from Russell Dam Site, which I undertook in September in accordance with a plan described in my letter of September 16, 1976. I regret that there has been so much delay in the completion of this work, but the extra time has allowed me first to obtain highly pure mineral separates for analysis and then to confirm the accuracy of the analytical work by duplicate analysis of most samples.

The report consists of four pages, as follows:

1. Summary of results on the primary samples from five stations
2. Summary of results on some additional samples
3. A table of analytical data
4. Comments on interpretation of the potassium-argon apparent ages.

The results reported herein are consistent with preliminary results reported to you by phone, with one exception. The preliminary result on the dike rock from station 21 + 15 was in error because of a mistake in my preliminary calculations. I am sorry for the error, but I am pleased to find that the correct result is consistent with your interpretation of the history of secondary alteration at the site.

I have enjoyed working with these interesting rock samples, and I thank you for the opportunity to carry out this study.

Sincerely,

Marion

J.M. Wampler
Associate Professor

JMW:cma
enclosures

SUMMARY OF RESULTS
(Primary Samples)

STATION	MATERIAL	POTASSIUM-ARGON APPARENT AGE*
19+20	Sericite, high purity. Separated by heavy liquids after disaggregation of sample	$295 \pm 6 \times 10^6 y$
20+95	Muscovite, high purity. Separated by heavy liquids after disaggregation of sample	$272 \pm 6 \times 10^6 y$
17+40	Feldspar (provided by Dr. Neiheisel)	$357 \pm 11 \times 10^6 y$
21+15	Whole rock sample of dike rock. Analytical sample was taken from the inner portion of the hand specimen, away from Mn-oxide stain or other surface alteration	$292 \pm 6 \times 10^6 y$
23+50	Whole rock sample of dike rock. Analytical sample was taken from a portion of the hand specimen showing little secondary alteration	$355 \pm 11 \times 10^6 y$

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*Apparent age is based on the following constants:

^{40}K decay constants: $\lambda_\beta = 4.72 \times 10^{-10} y^{-1}$

$\lambda_\varepsilon = 0.585 \times 10^{-10} y^{-1}$

$^{40}K/K = 0.000119$ (Atomic)

The indicated uncertainty in apparent age represents an estimate of the analytical precision at the 95% confidence level.

SUMMARY OF RESULTS
(Additional Samples)

STATION	MATERIAL	POTASSIUM-ARGON APPARENT AGE
19+20	Feldspar (very low potassium). Separated by heavy liquids after disaggregation of sample.	488 $\pm$ 20 $\times 10^9$y
20+95	Feldspar (low potassium). Separated by heavy liquids after disaggregation of sample.	293 $\pm$ 9 $\times 10^9$y
23+50	Whole rock sample of altered dike rock. Analytical sample was taken from an altered zone which extends about 1 cm on each side of a healed fracture through the hand specimen.	442 $\pm$ 35 $\times 10^9$y

ANALYTICAL DATA

STATION	MATERIAL	POTASSIUM (% by weight)	RADIOGENIC ARGON (% of total argon)	RADIOGENIC ARGON (STP nl/g)	APPARENT AGE (millions of years)
19+20	Sericite	8.72	99.2	111.2	
		8.60	99.2	109.7	
	Av.	8.66 ± 0.06		110.4 ± 1.6	295 ± 6
19+20	Feldspar	0.150	83.5	3.28	
		0.152	94.3	3.33	
	Av.	0.151 ± 0.004		3.30 ± 0.05	488 ± 20
20+95	Muscovite	8.71	99.1	102.3	
		8.68	99.6	101.3	
	Av.	8.70 ± 0.06		101.8 ± 1.4	272 ± 6
20+95	Feldspar	0.296 ± 0.005	92.8	3.74 ± 0.08	293 ± 9
17+40	Feldspar	0.348 ± 0.006	86.7	5.45 ± 0.11	357 ± 11
21+15	Whole rock	0.641	97.0	8.17	
		0.654	96.2	8.16	
	Av.	0.648 ± 0.007		8.16 ± 0.12	292 ± 6
23+50	Whole rock	0.470 ± 0.010	85.0	7.17 ± 0.14	355 ± 11
23+50	Altered zone	0.145 ± 0.010	78.1	2.68 ± 0.05	442 ± 35

COMMENTS ON INTERPRETATION OF POTASSIUM-ARGON AGES

Muscovite and Sericite: The potassium-argon apparent age of muscovite or sericite indicates the time elapsed since the mineral (last) became cool enough to retain argon (about 300°C). For igneous and hydrothermal mica, this time interval should be essentially the same as the age of the material unless there has been subsequent metamorphism. The potassium content of micas is sufficiently high that radiogenic argon which may have been incorporated at the time of formation is not normally significant.

Plagioclase Feldspar: Although plutonic K-feldspar is notorious for losing radiogenic argon, plagioclase feldspar normally behaves as a closed system for potassium and argon after its formation as part of igneous rocks. Therefore, the potassium-argon apparent age of plagioclase (from dolerites, for example) is often a good indicator of the age of igneous rocks which have not undergone metamorphism. However, for samples with very low potassium content, a small amount of initial radiogenic argon can be significant, making the apparent ages greater than the geologic age of the rock. The high apparent ages of the feldspar from station 19+20 and the altered dike rock from station 21+15 are probably due to the presence of initial radiogenic argon, since these samples have extremely low amounts of potassium.

Whole rocks: Potassium-argon apparent ages on whole-rock samples of igneous rock are reliable indicators of geologic age in favorable circumstances, and have been particularly useful for studies of mafic rocks (basalts and dolerites). Confirmation of the validity of whole rock ages requires multiple samples of unaltered rock. In the case of this work, the dike rock from station 21+15 is clearly different from the sample from station 23+50. The difference in apparent ages may be attributed to secondary alteration of the rock from station 21+15.

SECTION E

Patterson Branch Fault- Geologic Report

RICHARD B RUSSELL DAM AND LAKE

DESIGN EARTHQUAKE AND GEOLOGICAL HAZARD STUDY

PATTERSON BRANCH FAULT

PATTERSON BRANCH FAULT ---GEOLOGIC REPORT ------

CONTENTS:

FINAL GEOLOGIC REPORT, PATTERSON BRANCH FAULT, WILLINGTON SOUTH CAROLINA

1. PURPOSE: This study was undertaken to determine the activity of the Patterson Branch Fault relative to the Richard B Russell Dam and for the Design Earthquake study.

2. Methods: A week's field examination, consultation with outside principal investigators of the fault, geophysical examination, and trenching work was conducted. The map and geology of the area was done by Dr. Don Secor of the University of South Carolina, Columbia.

3. Physiography of the Patterson Branch area: Patterson Branch is a small creek draining into Clark Hill Reservoir. The Branch was a small tributary to the Savannah River. The area is one of multilevel terraces standing 65 feet above old bedrock grade of the Savannah River. The highest point in the positive relief is the accordant ridge and interfluve between Patterson Branch and the neighboring branch to the southeast.

4. Geology: There are 4 distinct geologic units underlying the Patterson Branch-Willington area. As mapped by Secor, the units are: mixed gneiss, hornblende gneiss, adamellite gneiss and the fourth is a mica schist lying to the southeast and northwest of the Secor units. Across the river the units are hornblende and granodiorite gneiss.

5. Recent Alluvium and Terrace:, Gravel caps lie on some terrace areas in the Patterson Branch area. In exploration for the base of these gravels it was discovered that an old buried stream channel of the Savannah River or its tributary lies beneath the terrace. See cross section on page 37.

6. Petrology: Core from boring PB-8 and PB-7 were examined at division laboratories for purposes of ascertaining description and cataclastic history.

PB-7 is described as a light grey, medium grained, adamellite gneiss. Although minor fragmentation of minerals is present, this rock does not constitute a cataclastic texture.

PB-8 is described as a greenish gray, fine to medium grained, foliated and cataclastic textured, hornblende granodiorite gneiss.

In addition a sample from the crushed quartz and feldspar mylonite zone was submitted for analysis. This unit is identified with the fault zone and hereafter will be called flinty crushed rock(FCR).

PBHS-1 (FCR) is described as quartz breccia occurring in a mylonitic host rock. For further expansion see the report on page 11, this report.

7. Geophysics: A magnetometer survey was conducted across the fault zone. The results of this survey are inconclusive, however this survey tends to validate the postulated structure.

8. Structure: The geologic structure of the area appears to be one of a core of adamellite centered in a anticline of hornblende gneiss. The southeast limb of the hornblende granodiorite gneiss is truncated by a fault zone whose surface expression is the flinty crushed rock zone. This zone pinches out successive units as they abut against the strike of the FCR. Relationships suggest a normal fault.

9. Fault Activity: Drilling and trenching were conducted to assess the activity of the fault. In an attempt to see if the base of the gravels were offset, exploratory drilling was conducted as a prelude to trenching. It was discovered at this time

that a confined water table exists in a remnant stream channel. The channel had been capped by saprolite. Upon removal of the cap, the artesian head rose to the pressure level of the lake. Since this removed the possibility of a trench the site next higher was chosen. As shown on the cross section, the terrace level gravels extend to some depth. The top of saprolite rock of the old channel has been downdroped as it traversed the fault. The trench was excavated across the fault in a bedrock - saprolite horizion. For discussion and analysis of the trench see the trip report and consultants summary on pages 6 through 10 of this report. The engineering geology map has the dimensions and description of the trench. The fault has been mapped to have a length of 7 ½ km.

Summary

In field examination and trenching the Patterson Branch appears to have no evidence of recent activity.

William E Hancock

William E. Hancock
Geologist, SASEN-FG

SASEN-FG 31 August 1976

SUBJECT: Trip Report to Modoc SC and Willington, SC

MEMORANDUM FOR RECORD

1. DATE: 21 July 1976

2. PURPOSE: To inspect and evaluate the proposed Patterson Creek-Willington Fault located along a NE linear trend extending from the shores of Clark Hill Reservoir south of Patterson Creek to Willington, South Carolina. Patterson Creek is located 7 miles SW of the Abbeville-McCormick County line on Clark Hill Reservoir.

3. PERSON MAKING TRIP:

William E. Hancock, Geologist, F&M Branch, Savannah

4. PERSON CONTACTED:

Donald Secor, Professor of Rock Mechanics and Geology, University of South Carolina

5. OBSERVATIONS:

The fault is postulated to be the causative mechanism for the Willington Earthquake of November 1974 - $M_b = 4.3$ by Talwani and Scheffler of the University of South Carolina. Don Secor did the detail Geology mapping of the area. Units defined by Secor are a admellite gneiss, hornblende gneiss, and a mixed gneiss. The fault trace is composed of a zone of flinty crushed quartz with comb structure. Diabase dykes and pegmatite dykes cut all three of these units but there is a notable decrease of the pegmatite dyke in the admellite gneiss. Field relationships of the units allow a fault interpretation; however, without the Willington earthquake, other structures could be postulated. Field mapping was done on the basis of residium and float rock. Criteria utilized was adequate for good control if conscience and hard work was employed.

6. CONCLUSIONS:

The existence of a structural fault, terminated as a Triassic basin basement fault, could be present in the area. The seismic activity might fall on this fault or on regional joint patterns associated in this area. This type of structure is common in the Piedmont and heretofore has not been associated with historic seismicity.

7. RECOMMENDATIONS:

The presence of a Pleistocene to Tertiary Savannah River gravel along the shoreline where the fault linear projects through could afford excellent control on recent movement. Therefore, this gravel should be:

a. Explored to develop subsurface profile (Time: one day).

b. If profile is such that the question of historic movement can be answered, the fault should be trenched to this location.

William E. Hancock
WILLIAM E. HANCOCK
Geology Section

SASEN-FG

16 November 1976

SUBJECT: Trip Report - Patterson Branch, Clark Hill Lake and Richard B. Russell - Diversion Channel

MEMORANDUM FOR RECORD

1. DATES: 13-14 November 1976

2. PURPOSE:

a. Inspection of trench excavated across the Patterson Branch Fault.

b. Inspection of Diversion Canal, Richard B. Russell Dam Site.

3. PERSONS MAKING TRIP:

Earl F. Titcomb, Jr., SASEN-FG
William E. Hancock, SASEN-FG

4. PERSON CONTACTED:

John McCracken, Resident Office Personnel, Richard B. Russell Project

5. OBSERVATIONS:

a. Trench - Patterson Branch . A trench was excavated approximately perpendicular to the N67E striking mylonite quartz breccia zone. This zone is postulated by Scheffler (1973) as a possible candidate for a causative mechanism in the 2 August 1974 Willington earthquake. Within the trench a 17-22.5' crushed quartz zone (1+10 - 1+30) was exposed. This quartz displayed an intense cataclastic nature. Splaying of minor 2 feet crushed quartz zones was commonly found on the NW side of the main crushed quartz zone. The right wall exposure shows a Graphic granite (0+25 - 0+50) dike truncating the splaying crush quartz. This granite pinches out in the floor and is not found along the left wall. Along the left wall and southeast of the main crushed quartz a slide developed. The wall sap material which the side is composed of shows no crushed quartz. The saprolite is zoned with multiple up to one inch wide layers of parallel grey clay. Interstitial to the layered clays are red saprolite most probably of hornblend granodiorite parentage. This slide saprolite displays "slickenside" and maganese staining. The slide is most probably caused by an unfavorable joint pattern. Predominate joint sets of N60W and vertical, N60W, 60NE and N55W 80NE was most unfavorable causing the walls to spall off into the trench. The slide area is further bound on the southeast left wall by a striking change in lithology. Along a N55W 80NE joint the slide is juxtaposed against a light

P. Scheffler (1973) Unpublished master thesis - The McCormick County, SC Earthquake of 2 August 1974

colored sap rock composed of hornblend granodiorite with zenoliths of adamellite gneiss. The hornblend granodiorite (hgn) shows flow of schistosity and foliation around the adamellite (adm). The hgn is heavily saprolitized while the adm is rather unaltered. The first few feet of this lithologic zone and particularly along the joints contain graphite in up to 6% composition. The graphite joints are slick.

b. The "A" soil horizon zone is leached of clay and is sandy. It is of lighter color and contrasts well with the underlying saprolite. No offsets were observed along this interface. Crushed quartz zones follow into the "A" horizon and concentrate along the surface. This zone also displays no offsets or disturbance of recent vintage.

c. Summary. The crushed mylonite breccia quartz zone was exposed along a 250 foot thru cut. The zone is one of extensive cataclastic rock. The fresher intruded and younger implaced rock is not as heavily saprolitized as the parent host rock of hornblend granodiorite gneiss. No offsets were found along continuous stratigraphic members. No offsets were found in the "A" soil horizons. Slickensides were present in the maganeese stained joints present in the Saprolite. These by themselves are not taken to be indicators of recent movement. (Picture 1, Figure 1 Included).

d. The Richard B. Russell Project was visited Sunday morning, 14 November 1976. Mr. McCracken was leaving the project office as we drove in. I briefly told him what we were planning, i.e. drilling in the Diversion Channel. The only work taken place was the dredging operation. The Construction Bridge area was visited. The pier footings within the channel had all been poured and the pier column forms were in place for Bent 2. Bent 4, adjacent to the landward side, had been constructed with the footing against the channel side. There did not appear to have been any work on the end bents since the date of my last visit (30 September 1976. The Contractor was drilling his blast hole pattern between approximately Sta. 20+50 and Sta. 22+50. It appeared that about one more lift would be required to bring the excavation to grade. Downstream of the fault along the right side a large pentacle of hard rock was left. This area was not yet drilled but the hole pattern was layed out. The fault zone was covered with debris throughout most of its length but the felsic dike could be seen in several places. Two tentative boring locations were selected at Sta. 18+50, ℄ and Sta. 20+00 along the right side.

5 Incl
as

WILLIAM E. HANCOCK
Geology Section

EARL F. TITCOMB, JR.
Chief, Geology Section

December 8, 1976

Mr. Earl F. Titcomb
U. S. Army Corps of Engineers
Box 889
Savannah, Georgia 31402

Dear Mr. Titcomb:

I am writing to summarize the results of my studies of the Patterson Creek fault in the recently excavated trench near the shore of Clark Hill Reservoir, southwest of Willington, South Carolina.

The country rock on both sides of the fault zone is hornblende granodiorite gneiss. In the block to the southeast of the fault zone this unit is more coarsely crystalline than in the northwest block. The northwestern block is cut by a few dikes and irregular masses of pegmatite and graphic granite. The southeastern block is cut by a felsite dike a few feet thick.

The main fault zone in the central part of the trench is an anastomosing series of dike-like masses of silicified fault breccia, striking northeast, with a near vertical dip. Angular clasts of incompletely silicified gouge or mylonite are locally present in the breccia. The country rock adjacent to the breccia zone appears to have undergone cataclasis.

In the block to the northwest of the fault zone numerous quartz veins of diverse orientation having comb structure occur. These are interpreted to be dilatational veins 1/ because of the comb structure, 2/ because they are not brecciated, and 3/ because they commonly cut each other without apparent lateral displacement. Near the northwestern end of the trench (0 + 50) a 1 foot thick vein of comb quartz occurs along the boundary between hornblende granodiorite gneiss and graphic granite. These relationships suggest either 1/ that a dilatational vein of comb quartz was emplaced along a pre-existing contact, or 2/ that the vein is a silicified fault zone along which lateral movement has juxtaposed the gneiss and graphic granite. I prefer interpretation 1/ because of the lack of brecciation in this particular vein. The dilatational comb quartz veins are most numerous in the northwestern block immediately adjacent to the fault zone. The frequency of occurrence of comb quartz veins decreases to the northwest, and at the northwest end of the trench only a few thin veins are present. In my experience, comb quartz and silicified fault breccia occur together along the entire known extent of the Patterson Creek fault. These facts suggest that the two are genetically related and formed together at the same time while the fault was active.

In the northwestern block the quartz veins with comb structure are offset by several small northwest striking faults. Some structural data on these are given in Table I. In most cases the strike separationof small quartz veins offset by these faults are one inch or less One particular fault, located on the southwestern face of the trench between stations 0 + 68 and 0 + 82, has offset two veins of different orientation in such a way as to suggest combined reverse and left lateral strike slip movement of six inches. The direction of net slip

TABLE I

STATION	FAULT ATTITUDE	SLICKENSIDE ATTITUDE	ATTITUDE AND STRIKE SEPARATION OF OFFSET COMB QUARTZ VEINS
0 + 63 (SW Wall)	N8W84SW		N76E83SE 1" left lateral
0 + 68 to 0 + 82 (SW Wall)	N8W43NE	26N30E	N25E50NW 10½" left lateral N62E78NW 6½" left lateral
0 + 66 (NE Wall)	N51W60NE	36S76E	
0 + 67 (NE Wall)	N24W71NE	6S27E	½" right lateral
0 + 83 (NE Wall)	N60W55NE	2 [illegible]375E	½"left lateral

calculated for this fault from the above data is 18S28E whereas the orientation of the slickensides in the fault plane is 26N30E. In order to explain the lack of coincidence between the slickenside direction and the net slip direction it seems necessary to postulate two or more episodes of slip at different times and in different directions. In spite of the uncertainty concerning the nature of the movement on the northwest trending faults, they appear to be later than the Patterson Creek fault because they cut comb quartz veins that are genetically related to movement on the Patterson Creek fault.

In conclusion, I could find no evidence for recent movement along the Patterson Creek fault. The boundary between the A and B soil horizons passes over the fault zone without apparent offset. Crosscutting relationships exposed in the trench suggest that the Patterson Creek fault is inactive and is cut by a younger set of northwest striking faults of very small displacement. The age of these northwest striking faults is not known. The continuity of northeast trending geological contacts in the area between Clark Hill Reservoir and Willington, when mapped on a scale of 1 : 24,000, suggests to me that if major northwest trending faults are present in this area their strike separation is less than a few hundred feet.

Please let me know if I can be of any additional assistance in this matter.

Sincerely yours

Donald T. Secor, Jr

Donald T. Secor, Jr.

U.S. ARMY ENGINEER DIVISION LABORATORY, SOUTH ATLANTIC CORPS OF ENGINEERS MARIETTA, GEORGIA PETROGRAPHIC REPORT			DISTRICT Savannah PROJECT RICHARD B. RUSSELL DAM CONTRACT NO. ---
SOURCE Patterson Branch Seismic Zone Hole PB7 and PB8		LAB NO. 232/940 - 942	DATE REPORTED 11 November 1976
DATE RECEIVED 20 October 1976	REQ. NO.	EN-FG-13	WORK ORDER NO. 0271

PATTERSON BRANCH SEISMIC ZONE ROCK SAMPLES

Petrographic and/or X-ray diffraction analyses have been made in accordance with CRD-C 127-67 and or EM 1110-2-2000. Thin section studies, petrographic oil immersion studies, and megascopic examination have been performed as necessary for evaluation procedures and photomicrographs of thin sections, where applicable, appear as figures in the report. X-ray diffraction techniques, if applicable to this testing, include ethelene glycol and heat treatment of sedimented slides as corroborative diagnostic tests to the powder press technique, and X-ray diffractograms appear as plates. Other tests necessary for this investigation are described in the report.

Detailed petrographic descriptions and pertinent remarks regarding acceptance of individual rock types, soils, or fine aggregate and other earth materials are included in the tables. The summary below presents key data resulting from the testing.

9 Incl
- 6 Figures (3 pages)
- 3 Plates
- Tables

SUMMARY

Petrographic and X-ray diffraction analysis of two (2) rock cores from Patterson Branch Seismic Zone and a field sample of comb structured vein quartz and quartz breccia from a shear zone has been made to provide information on rock fabric for purposes of correlation with the stress history of rock formations in this area.

The rock core from 59.3 to 60.2 feet depth of boring PB-7 is a light grey, medium grained, adamellite gneiss (see Figure 1). Mineral composition of this rock, based on X-ray diffraction and thin section analysis, approximates the following (see Plate 1).

Average Percent Mineral Composition

Plagioclase Feldspar	35
K-Feldspar (Microcline)	15
Quartz	30
Hornblende	8
Biotite	7
Magnetite	3
Other (Garnet, etc.)	2

App 3
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Section E

REPORTED BY: ■ PHONE ☐ WIRE DATE 9 Nov 1976, Neiheisel to Hancock	TESTED BY JN	CHECKED BY RJS
	SAMPLED BY W. E. Hancock	

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Previous editions of this form are obsolete.

Thin section analysis reveals an interlocking-granular, granoblastic texture of average 1 mm grain size (see Figure 2). Although minor fragmentation of minerals is widespread, this rock fabric does not constitute a cataclastic texture. Foliation is not apparent in this granofels gneiss. Twinning of feldspars indicates varieties of andesine and oligioclase in the measured albite twinning extinction angles of the plagioclase feldspar grains. Microcline is the K-feldspar variety as disclosed by the characteristic "grid-iron" twinning of this mineral (see Figure 2). Quartz is generally finer grained than the feldspars and occurs interstitually between feldspar. Ferromagnesian minerals include both green hornblende and black biotite which occur in patchy distribution throughout the groundmass. Porphyroblasts of hornblende range to 5 mm size. Local black magnetite and pink garnet range up to 2 mm grain size and occur disseminated as minor accessory minerals in the groundmass.

The rock core from 54.5 to 55.2 feet depth of boring PB-8 is a greenish grey, fine to medium grained, foliated, slightly weathered, cataclastic textured, hornblende granodiorite gneiss (see Figure 3). Mineral composition of this rock core, based on X-ray diffraction and thin section analysis, approximates the following (see Plate 2).

Average Percent Mineral Composition

Plagioclase Feldspar	35
Quartz	30
Hornblende	10
Biotite	10
Chlorite	7
Epidote	5
Magnetite	1
Other (Pyrite, etc.)	2

Thin section analysis reveals a cataclastic texture comprised of a granulated groundmass of fragmented and rotated feldspar, quartz, and ferromagnesian minerals (see Figure 4). Local yellow epidote occurs in proximity to hornblende and chlorite in the groundmass. This rock type does not appear to be a compositional variety of the rock core from boring PB-7; chief differences include greater and more varied ferromagnesian minerals, lesser amounts of K-feldspar and more abundant plagioclase feldspar.

The tan, brittle, surface float rock, field sample PBHS-1, obtained from the zone postulated by Scheffler (1976) as the fault zone which might be responsible for the 1974 Mb 4.3 earthquake southeast of the Richard B. Russell dam site is a comb quartz and quartz breccia specimen (see Figure 5). This rock fits the description of Scheffler's "10-m width of comb quartz, quartz breccia, and quartz mylonite". The quartz breccia could be described as a quartz mylonite which formed at an earlier time than the comb quartz which occurs in the mylonite host rock as a younger feature with distorted quartz crystals facing toward the center and forming the quartz structure (see Figure 6). Conley and Drummond (1965) also consider such mylonite with comb quartz to be a result of a brecciation and vein filling by crystalline quartz occurring

much later than the mylonitization. They attribute the time of the later brecciation of the ultramylonite as coincident with the development of the Blue Ridge front during Tertiary time with the vertical movement along older Triassic faults. The reason the Tertiary age is assigned lies in the fact that one of the ultramylonite zones occurs at the base of the Blue Ridge front in the area where W. A. White (1950) proposed the existence of a Tertiary normal fault that can be traced over 700 miles by following six systematic left handed offsets of 2 to 10 miles displacement. The Triassic age of the quartz mylonite, which hosts the brecciated quartz and comb quartz, is assigned because this rock is clearly younger than the latest period of Inner Piedmont deformation and because these rocks (a) transect regional folds and tectonic foliations, (b) are not offset by younger faults, and (c) show no evidence of having been metamorphosed. The brecciation and vein filling producing the comb structure (Figure 6) formed at a later date postulated as Tertiary time which seems reasonable in light of existing evidence cited and that it is coincident with development of the Blue Ridge front of Tertiary time. It is worth pointing out, however, that the time between the Triassic and Tertiary time, approximately 115 million years, is a long duration and the Tertiary age constituting the upper time interval comprises nearly 60 million years. Thus, the age of this fault, to which no absolute date has been assigned, could be very ancient.

References Cited

Conley, J. F., and Drummond, K. M., 1965, Ultramylonite zones in the western Carolinas: Southeastern Geology, v. 6, p. 201-211.

Scheffler, P. K., 1976, The McCormick County, South Carolina, earthquake of 2 August, 1974: Geological and geophysical investigations; Unpublished M. S. thesis, University of South Carolina.

White, W. A., 1950, Blue Ridge Front, A Fault Scarp: Bull. Geol. Soc. America, v.61, p. 1309 - 1346.

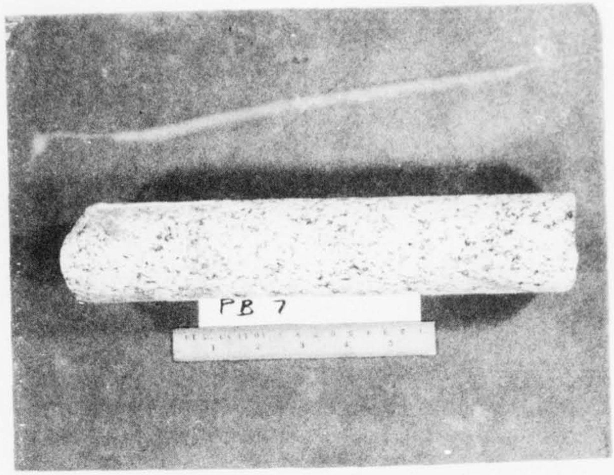

Figure 1. Rock core of grey, medium to coarse grained, slightly weathered, interlocking-granular adamellite gneiss from 59.3 to 60.2 feet depth of boring PB-7, Patterson Branch Seismic Zone. This granoblastic tedtured rock displays but minor metamorphic characteristics. (SADL 232/940).

Figure 2. Photomicrograph (50X, Crossed Nicols) of thin section of adamellite gneiss from 59.3 ft. depth of boring PB-7 showing interlocking granoblastic texture and discrete albite twinning (top) in plagioclase feldspar and "grid-iron" twinning in microcline (lower right). (SADL 232/940)

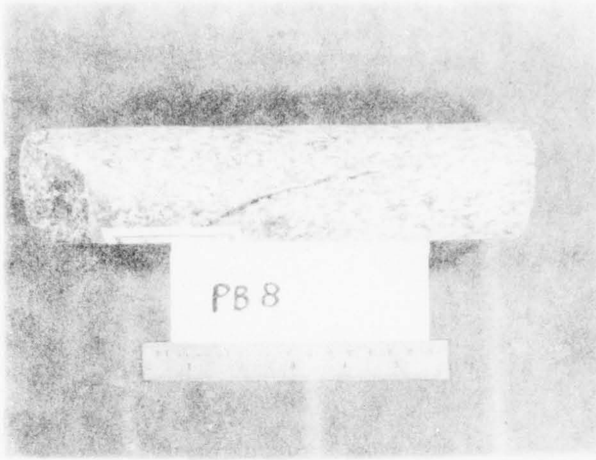

Figure 3. Hornblende gneiss from 54.5 to 55.2 feet depth of boring PB-8, Patterson Branch Seismic Zone. Dark lineated minerals consist of hornblende biotite and chlorite in a groundmass of feldspar and quartz. The genetic classification of this rock unit is hornblende granodiorite gneiss. (SADL 232/941).

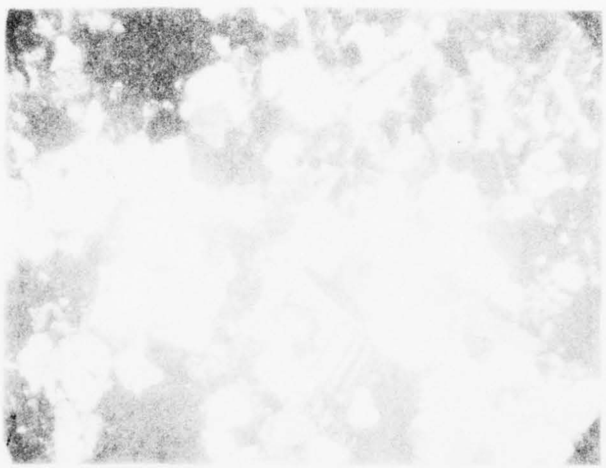

Figure 4. Photomicrograph (50X, Crossed Nicols) of thin section of hornblende gneiss from 55 feet depth of boring PB-8 showing granulated nature of the interlocking granular and lineated groundmass. Local twinning is observed in some of the feldspars of this cataclastic textured rock. (SADL 232/941)

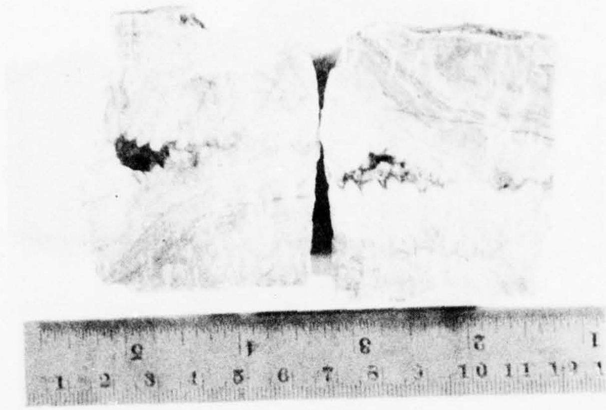

Figure 5. Quartz vein and quartz breccia from shear zone near Patterson Branch Seismic Zone with quartz vein showing comb structure and open cavity and local banded quartz (onyx). (SADL 282/942)

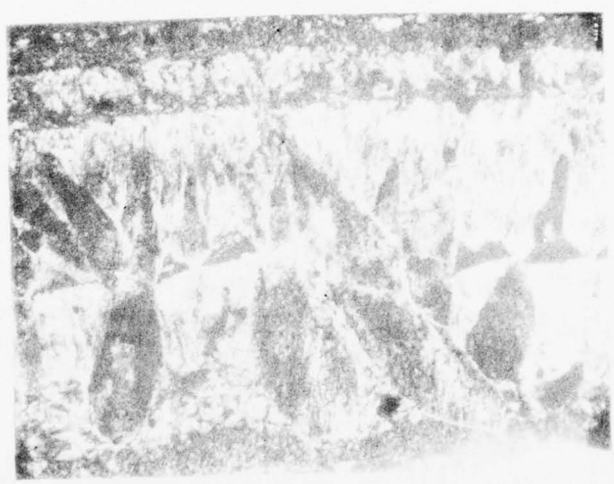

Figure 6. Photomicrograph (50X, Crossed Nicols) of thin section of quartz vein shown in Figure 5. Comb structure occurs at right angles to banding in this fissure filling which occurs in the most deformed rock in the area. (SADL 282/942).

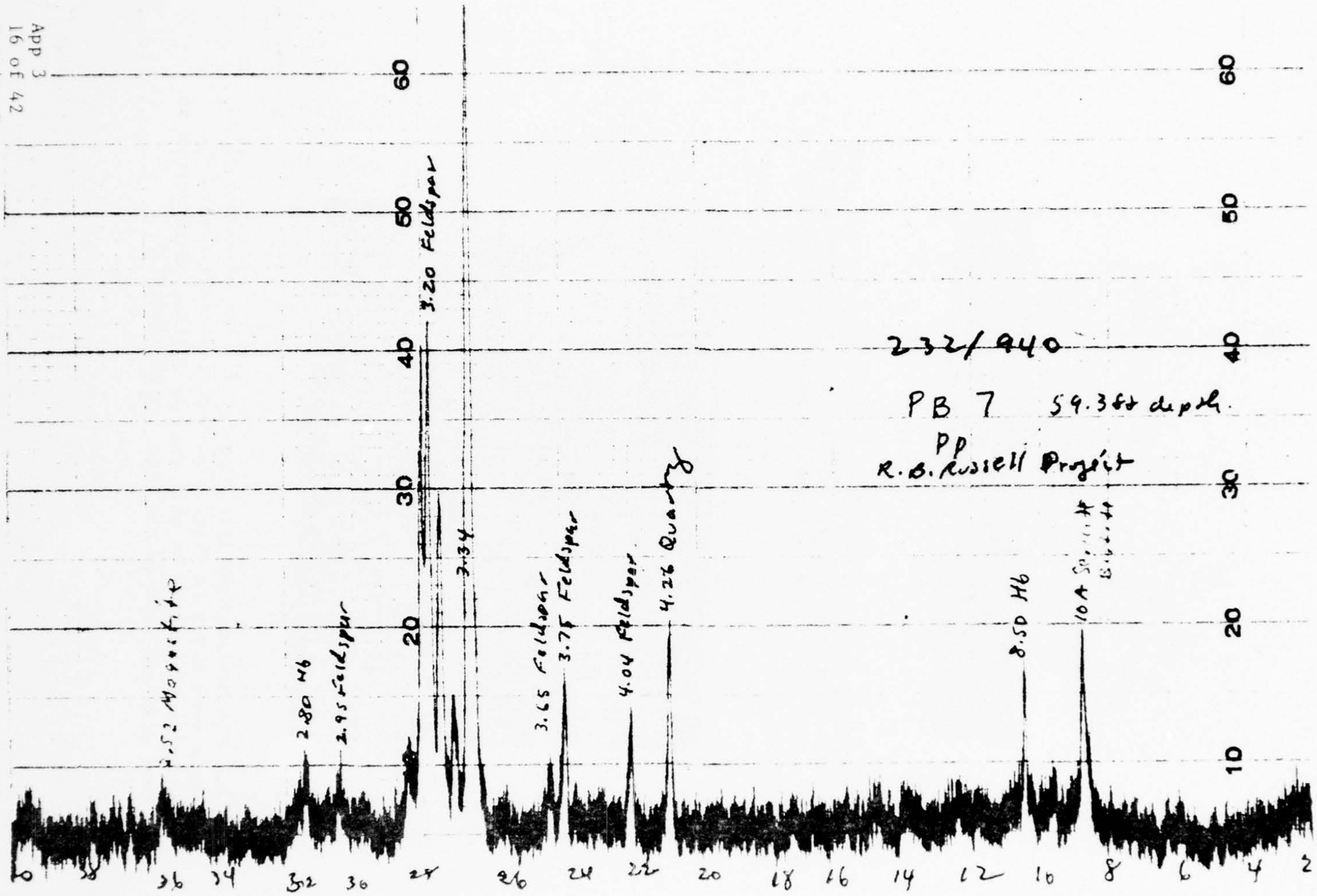

Plate 1. X-ray diffractogram of powder press sample of gneiss from 59.3 ft. depth of core hole PB-7. (SADL 232/940)

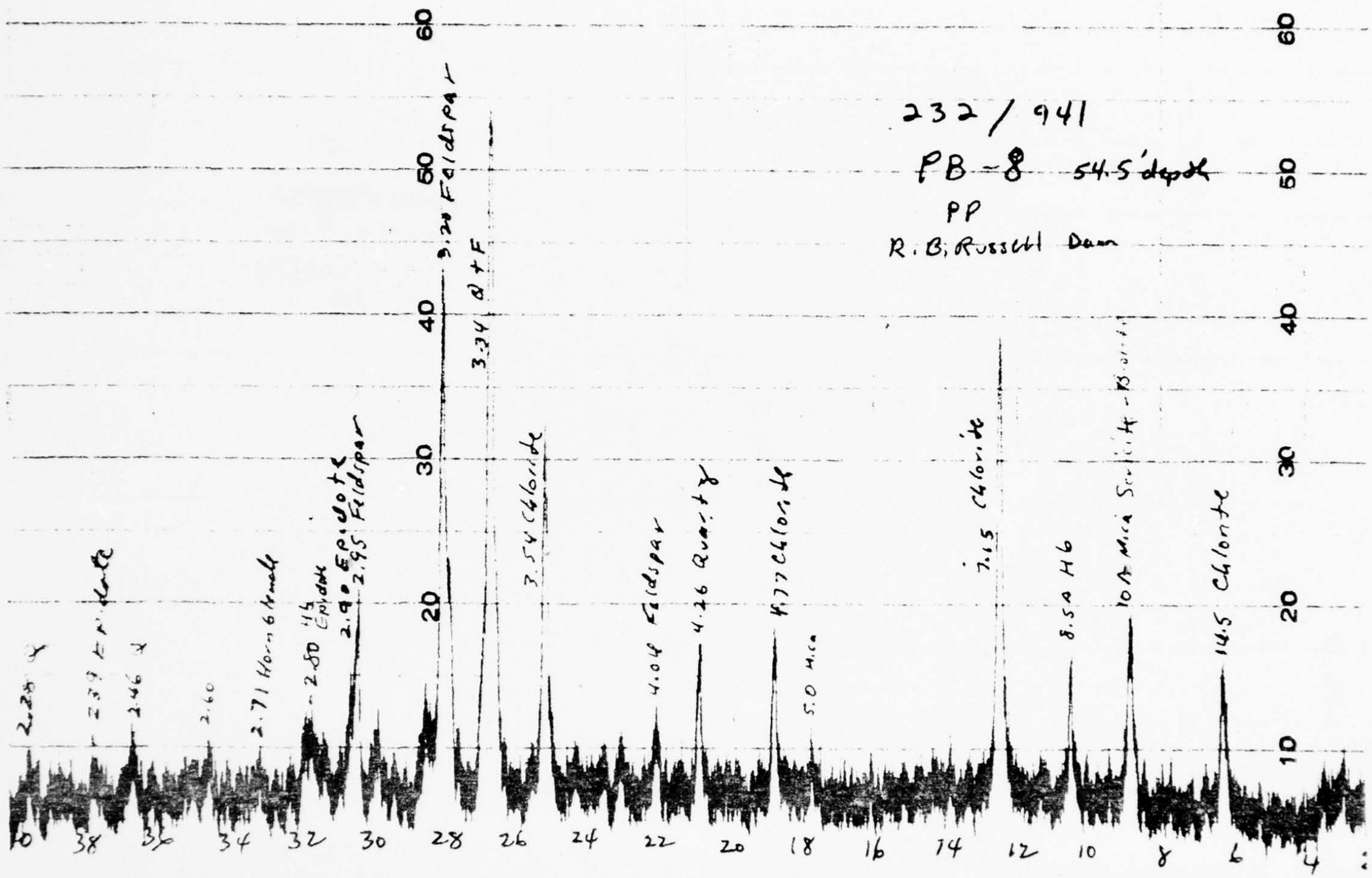

Plate 2. X-ray diffractogram of powder press sample of gneiss from 54.5 ft. depth of core hole PB-8. (SADL 232/941)

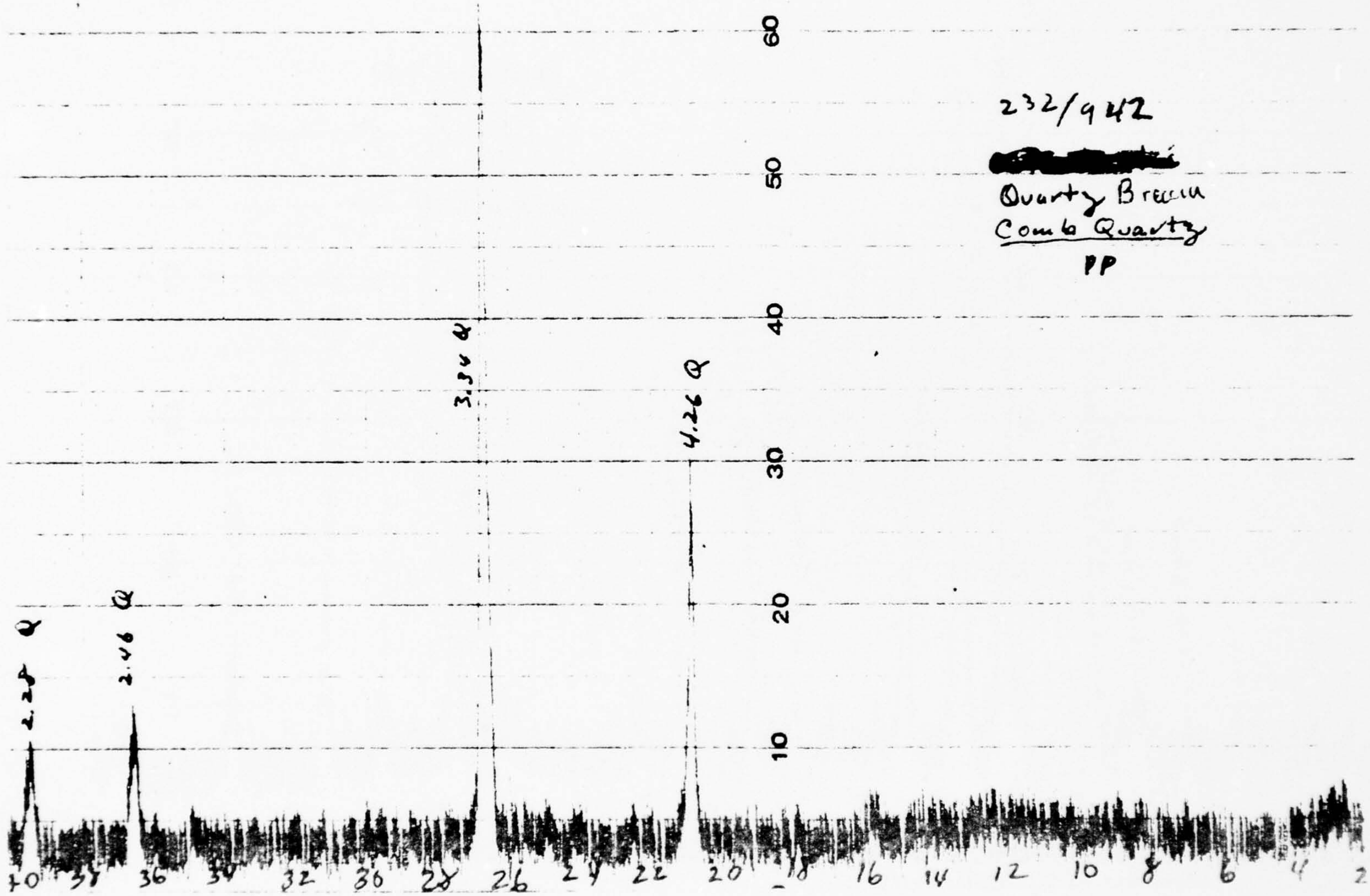

Plate 3. X-ray diffractogram of powder press sample of quartz breccia from Patterson Branch Seismic Zone. (SADL 232/942)

Hole No. PB-1

DRILLING LOG	DIVISION South Atlantic	INSTALLATION Richard B Russell Dam and Lake	SHEET OF SHEETS
1. PROJECT Design Earthquake and Hazard Study		10. SIZE AND TYPE OF BIT standard splitspoon	
2. LOCATION (Coordinates or Station) Patterson Branch Fault		11. DATUM FOR ELEVATION SHOWN (TBM or MSL) MSL	
3. DRILLING AGENCY Savannah District		12. MANUFACTURER'S DESIGNATION OF DRILL 314 Failing	
4. HOLE NO. (As shown on drawing title and file number)	PB-1	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN	DISTURBED 1 / UNDISTURBED
5. NAME OF DRILLER P. Roundtree		14. TOTAL NUMBER CORE BOXES	
6. DIRECTION OF HOLE xxx VERTICAL ☐ INCLINED ____ DEG. FROM VERT.		15. ELEVATION GROUND WATER 336.0'	
		16. DATE HOLE	STARTED 17 Sept 76 / COMPLETED 17 Sept 76
7. THICKNESS OF OVERBURDEN 11.0'		17. ELEVATION TOP OF HOLE 339.2'	
8. DEPTH DRILLED INTO ROCK		18. TOTAL CORE RECOVERY FOR BORING %	
9. TOTAL DEPTH OF HOLE 11.0'		19. SIGNATURE OF INSPECTOR William E. Hancock, Geologist	

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
339.2'	0		SC-CL, Red to yellow and tan layered clayey sand and lean clay. 6 inch layer of surface cobbles and gravels			w.t.
	5		SC, tan clayey sand			
			CH, Red and tan fat clay w/ gravel clasts		1	W.T. ______ Water table reading ______ hrs. after hole completed.
	10		SC, Red to tan, clayey sand with pea gravel @ 7.5'			
			MH, Yellow to tan saprolite			W.T. ______ Date ______ Depth to water during drilling
			bottom of hole at 11.o ft.			
			NOTE: Soils field classified in accordance with the Unified Soil Classification System.			

Hole No. PB-1A (PA-1)

DRILLING LOG	DIVISION South Atlantic	INSTALLATION Richard B Russell Dam & Lake	SHEET 1 OF SHEETS

1. PROJECT Design Earthquake and Hazard Study	10. SIZE AND TYPE OF BIT Auger
2. LOCATION (Coordinates or Station) Patterson Branch Fault	11. DATUM FOR ELEVATION SHOWN (TBM or MSL) MSL
3. DRILLING AGENCY Savannah District	12. MANUFACTURER'S DESIGNATION OF DRILL Beaver, Portable
4. HOLE NO. (As shown on drawing title and file number) (PA-1) PB-1A	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED 7; UNDISTURBED
5. NAME OF DRILLER Hancock	14. TOTAL NUMBER CORE BOXES
6. DIRECTION OF HOLE XXX VERTICAL ☐ INCLINED ___ DEG. FROM VERT.	15. ELEVATION GROUND WATER 336'
7. THICKNESS OF OVERBURDEN 10'	16. DATE HOLE: STARTED 8/4/76; COMPLETED 8/4/76
8. DEPTH DRILLED INTO ROCK 0	17. ELEVATION TOP OF HOLE 340.5'
9. TOTAL DEPTH OF HOLE 10'	18. TOTAL CORE RECOVERY FOR BORING %
	19. SIGNATURE OF INSPECTOR William E Hancock, Geologist

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
340.5	0		CL, red, lean sandy clay		1	
			GM, red, silty gravels in sandy silty matrix. clasts are pea to pbl. size.		2	sample 3 fm 2.5'-3.0'
	5				4	sample 5 fm4.75'-5.3'
			CL, variegated red, yellow micaceous lean clay		6	
			GC, yellow, gravels in clay and mica matrix, large pbl size.			W.T. 4.5' Date 8/4/76 Depth to water during drilling
	10		MH, silver orange, silty clay saprolite. structureless		7	
			bottom of hole 10.0'			W.T. 4.5' Water table reading 24 hrs. after hole completed.
	15					

NOTE: Soils field classified in accordance with the Unified Soil Classification System.

Hole No. P B -2

DRILLING LOG	DIVISION South Atlantic	INSTALLATION Richard B. Russell Dam & Lake	SHEET 1 OF SHEETS

1. PROJECT Design Earthquake and Hazard Study	10. SIZE AND TYPE OF BIT standard splitspoon
2. LOCATION (Coordinates or Station) Patterson Branch Fault	11. DATUM FOR ELEVATION SHOWN (TBM or MSL) MSL
3. DRILLING AGENCY Savannah District	12. MANUFACTURER'S DESIGNATION OF DRILL 314 Failing
4. HOLE NO. (As shown on drawing title and file number) PB 2	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED 4; UNDISTURBED
5. NAME OF DRILLER P Roundtree	14. TOTAL NUMBER CORE BOXES
6. DIRECTION OF HOLE: XX VERTICAL ☐ INCLINED ____ DEG. FROM VERT.	15. ELEVATION GROUND WATER 321.8'
	16. DATE HOLE: STARTED 20 Sept 76; COMPLETED 20 Sept 76
7. THICKNESS OF OVERBURDEN 29.9'	17. ELEVATION TOP OF HOLE 342.8'
8. DEPTH DRILLED INTO ROCK 0	18. TOTAL CORE RECOVERY FOR BORING %
9. TOTAL DEPTH OF HOLE 29.9'	19. SIGNATURE OF INSPECTOR William E. Hancock, Geologist

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g	BLOW
342.8'	0		SC, Red, yellow and tan, clayey fine grained sand w/ maganese -iron cemented sand nodules (wad)			W.T. 10.0' Water table reading 24 hrs. after hole completed.	
	5		Tan and gray lean clayey sand			W.T. 20.0' Date 20 Sept 76 Depth to water during drilling	
			CL, Brown and tan, lean sandy clay.		1		
	10						
			SC, Black, wad layer				
	15		CH, Purple and gray, fat clay w/ flinty crushed rock (FCR) and a few pea size gravel clasts - silt layer - kaoline clays		2		
	20					w.t.	
			SP, tan to gray, kaoline water bearing sands medium grained micaceous sands			NOTE: Soils field classified in accordance with the Unified Soil Classification System.	
	25						
			MH, tan silt, structured saprolite, quartz-biotite- hornblende-gnesiss		3		62
							38
					4		40
	29.9'		refusal to splitspoon				
			bottom of hole 29.9'				

Hole No. PB-3

DRILLING LOG	DIVISION South Atlantic	INSTALLATION Richard B. Russell Dam& Lake	SHEET 1 OF 1 SHEETS

1. PROJECT Design Earthquake & Hazard Study	10. SIZE AND TYPE OF BIT Standard splitspoon
2. LOCATION (Coordinates or Station) Patterson Branch Fault	11. DATUM FOR ELEVATION SHOWN (TBM or MSL) MSL
3. DRILLING AGENCY Savannah District	12. MANUFACTURER'S DESIGNATION OF DRILL 314 Failing
4. HOLE NO. (As shown on drawing title and file number) PB-3	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN — DISTURBED 16 — UNDISTURBED
5. NAME OF DRILLER P. Roundtree	14. TOTAL NUMBER CORE BOXES
6. DIRECTION OF HOLE X VERTICAL ☐ INCLINED ____ DEG. FROM VERT.	15. ELEVATION GROUND WATER 330.2'
	16. DATE HOLE — STARTED 22 Sept 76 — COMPLETED 22 Sept 76
7. THICKNESS OF OVERBURDEN 33.0'	17. ELEVATION TOP OF HOLE 345.19
8. DEPTH DRILLED INTO ROCK 0	18. TOTAL CORE RECOVERY FOR BORING %
9. TOTAL DEPTH OF HOLE 33.0'	19. SIGNATURE OF INSPECTOR William E Hancock, Geologist

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g	BLOW
345.2'	0		CL, Red and gray, sandy lean clay.			W.T. 14.2' Water table reading 24 hrs. after hole completed.	7, 12, 15
	5		-layered red and gray clayey sand and lean clay		1	W.T. 20.0' Date 22 Sept. 76 Depth to water during drilling	24, 29, 30
	10		-layered with fat clay -fragments of flinty crushed rock included (FCR)		2		36, 45, 38, 39
	15		CL-ML, tan and gray layered silt and micaceous lean clay w/ FCR		Continuously sampled @ 1.5 ft. intervals	w.t.	38, 40, 39
	20		SC, Red medium grained micaceous sand& clayey sand.				18
			MH-GP, tan, layered lignitic silt and pebble size gravels.				27, 44
	25		MH, Tan saprolite, structured quartz-biotite-hornblende gneiss				46, 47, 51
	30		refusal to splitspoon @ 33.0'			NOTE: Soils field classified in accordance with the Unified Soil Classification System.	68, 100/5, 100/6
			Bottom of hole 33.0'				

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Section E

Hole No. PB-4

DRILLING LOG	DIVISION South Atlantic	INSTALLATION Richard B Russell Dam& Lake	SHEET 1 OF 1 SHEETS

1. PROJECT: Design Earthquake and Hazard Study	10. SIZE AND TYPE OF BIT: Standard splitspoon
2. LOCATION (Coordinates or Station): Patterson Branch Fault	11. DATUM FOR ELEVATION SHOWN (TBM or MSL): MSL
3. DRILLING AGENCY: Savannah District	12. MANUFACTURER'S DESIGNATION OF DRILL: 314 Failing
4. HOLE NO. (As shown on drawing title and file number): PB-4	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED / UNDISTURBED
5. NAME OF DRILLER: P. Roundtree	14. TOTAL NUMBER CORE BOXES
6. DIRECTION OF HOLE: xxxxx VERTICAL ☐ INCLINED ____ DEG. FROM VERT.	15. ELEVATION GROUND WATER 327.8'
	16. DATE HOLE: STARTED 22Sept 76; COMPLETED 22 Sept 76
7. THICKNESS OF OVERBURDEN 30.0'	17. ELEVATION TOP OF HOLE 340.8'
8. DEPTH DRILLED INTO ROCK 0	18. TOTAL CORE RECOVERY FOR BORING %
9. TOTAL DEPTH OF HOLE 30.0'	19. SIGNATURE OF INSPECTOR: William E Hancock, Geologist

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g	BLOWS
340.8'	0		CL, Tan lean clay with fine grained sand.	CONTINUOUS SAMPLE TAKEN		W.T. 7.9' Water table reading 24 hrs. after hole completed.	6, 10
	5		SC, tan and red, layered sand and clayey sand.				24, 29
			CL, mottled red, gray and tan, lean sandy clay -layer of pea gravel			W.T. 13' Date 22 Sept. 76 Depth to water during drilling	32, 35, 42
	10		SC, red and gray, medium to coarse grained clayey sand w/ streaks of pea gravel.			w.t.	38, 35
	15		CL, gray, lean clay w/ fat streaks and fragments of flinty crushed rock(FCR)				22, 43, 40
			SP, gray, medium grained kaoline sand and mica				30
	20		CL, gray, sandy clay & mica				27
			SP, gray, water bearing sand with trace of kaoline and mica.				24, 6
	25		SP/ MH, gray coarse sand layered with mica and silt. @ 24.0-25.5 auger picked up large gravel clasts.			NOTE: Soils field classified in accordance with the Unified Soil Classification System.	50, 59, 58, 55
	30		MH, Tan, blocky silt w/ saprolite structure of quartz-feldspar-biotite hornblende gneiss. @ 30.0 ' refusal to splitspoon & botton of hole				

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Section E

Hole No. PB-5

DRILLING LOG	DIVISION South Atlantic	INSTALLATION Richard B Russell Dam and Lake	SHEET 1 OF SHEETS

1. PROJECT Design Earthquake and Hazard Study	10. SIZE AND TYPE OF BIT standard splitspoon
2. LOCATION (Coordinates or Station) Patterson Branch Fault	11. DATUM FOR ELEVATION SHOWN (TBM or MSL) MSL
3. DRILLING AGENCY Savannah District	12. MANUFACTURER'S DESIGNATION OF DRILL 314 Failing
4. HOLE NO. (As shown on drawing title and file number) PB-5	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN — DISTURBED — UNDISTURBED
5. NAME OF DRILLER P. Roundtree	14. TOTAL NUMBER CORE BOXES
6. DIRECTION OF HOLE XX VERTICAL ☐ INCLINED ____ DEG. FROM VERT.	15. ELEVATION GROUND WATER 313.2'
	16. DATE HOLE — STARTED 23Sept76 — COMPLETED 23Sept 76
7. THICKNESS OF OVERBURDEN 30	17. ELEVATION TOP OF HOLE 340.0'
8. DEPTH DRILLED INTO ROCK 0	18. TOTAL CORE RECOVERY FOR BORING %
9. TOTAL DEPTH OF HOLE 30	19. SIGNATURE OF INSPECTOR William E. Hancock

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g	BLOW
340'	0		SC, Tan, silty clayey sand, fine grained -variegated tan, gray and red			W.T. 8.2' Water table reading 24 hrs. after hole completed. W.T. 16.8' Date 23 Sept. 76 Depth to water during drilling	5, 14, 32, 34, 34
	5						
			CL, Tan, gray and red lean clay, sandy. -mottled red and gray				29, 30
	10		CL-ML, Mottled tan and red micaceous lean clay w/ lignitic layers				27, 32
			ML-SC, Gray kaoline sand layered in silt				28
	15		SC gray, micaceous, kaoline sand and silt, coarse grained to pea gravel in size w/ lignite layers tan, silt layer				28, 24, 15
	20		GM-ML, tan gravel layered with silt. Gravel comes in streaks				13, 10, 18
	25		ML- silt, tan w/ occasional lignite streaks.				22
			MH Green to tan highly micaceous saprolite. (structureless) refusal to splitspoon @ 30.0'				61, 62, 66
	30		Bottom of hole				

NOTE: Soils field classified in accordance with the Unified Soil Classification System.

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Section E

Hole No. PB-6

DRILLING LOG	DIVISION SOUTH ATLANTIC	INSTALLATION Richard B Russell Dam & Lake	SHEET 1 OF SHEETS

1. PROJECT Design Earthquake and Hazard Study	10. SIZE AND TYPE OF BIT Std. Splitspoon
2. LOCATION (Coordinates or Station) Patterson Branch Fault	11. DATUM FOR ELEVATION SHOWN (TBM or MSL) MSL
3. DRILLING AGENCY Savannah District	12. MANUFACTURER'S DESIGNATION OF DRILL 314 FAILING
4. HOLE NO. (As shown on drawing title and file number) PB 6	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN — DISTURBED 4 — UNDISTURBED
5. NAME OF DRILLER P. Roundtree	14. TOTAL NUMBER CORE BOXES 0
6. DIRECTION OF HOLE XXX VERTICAL ☐ INCLINED ____ DEG. FROM VERT.	15. ELEVATION GROUND WATER 328'
	16. DATE HOLE — STARTED 24Sept76 — COMPLETED 24 Sept 76
7. THICKNESS OF OVERBURDEN 34.5'	17. ELEVATION TOP OF HOLE 339'
8. DEPTH DRILLED INTO ROCK 0	18. TOTAL CORE RECOVERY FOR BORING %
9. TOTAL DEPTH OF HOLE 34.5'	19. SIGNATURE OF INSPECTOR William E. Hancock, Geologist

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
339'	0		SM-C, Brown to tan, fine grain silty sand with layers of clayey sand.			W.T. 3.0' Water table reading 24 hrs. after hole completed.
	5		SC , red and gray clayey sand		1	W.T. 11.0' Date 24 Sept 76 Depth to water during drilling
	10		Cl , red-purple and gray lean sandy clay. @10.5 change to SC-Cl		2	
	15		SC , Tan, yellow and gray clayey sand w/ fragments of feldspar and quartz. Possible flinty crushed rock fragments also. -grey w/ streaks of red FCR in lean clay matrix tan, structureless lean sandy clay w/ mica		3	
	20		CH , Gray, fat clay w/ trace of organics, FCR present -lignite material layered in fat clay, increasing mica content		4	
	25		MH , tan, highly micaceous fat silt layered w/ lignite		5	
	30		SM , Tan, fine grained micaceous sand, silty. tan sandy silty gravel			

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Section E

NOTE: Soils field classified in accordance with the Unified Soil Classification System.

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE 339'		Hole No. PB-6	
PROJECT Design Earthquake and hazard study	INSTALLATION Richard B. Russell Dam & Lake		SHEET 2 OF SHEETS	

ELEVATION	DEPTH	LEGEND	CLASSIFICATION OF MATERIALS (Description)	% CORE RECOVERY	BOX OR SAMPLE NO.	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant)
308'	30	c	d	e	f	g
			continued from page 1. , tan sandy silty gravel			
			ML , tan silt w/ some rock fragments			
			@ 33.0' refusal in silt w saprolite structure indicating quartz-mica-hornblende gneiss, saprolite very sandy, tan in color.			
			Bottom of the hole at 34.5 ft elevation of bed rock 307.5'.			

AD-A043 849 ARMY ENGINEER DISTRICT SAVANNAH GA F/G 8/11
GEOLOGICAL AND SEISMOLOGICAL EVALUATION OF EARTHQUAKE HAZARDS A--ETC(U)
MAR 77 W E HANCOCK, E F TITCOMB

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Hole No. PB-7

DRILLING LOG	DIVISION: South Atlantic	INSTALLATION: Richard B Russell Dam and Lake	SHEET 1 OF SHEETS

1. PROJECT: Design Earthquake and Hazard Study	10. SIZE AND TYPE OF BIT: NX & standard splitspoon
2. LOCATION (Coordinates or Station): Patterson Branch Fault	11. DATUM FOR ELEVATION SHOWN (TBM or MSL): MSL
3. DRILLING AGENCY: Savannah District	12. MANUFACTURER'S DESIGNATION OF DRILL: 314 Failing
4. HOLE NO. (As shown on drawing title and file number): PB-7	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED 24 ; UNDISTURBED
5. NAME OF DRILLER: R. Roundtree	14. TOTAL NUMBER CORE BOXES: 1
6. DIRECTION OF HOLE: xxxx VERTICAL ☐ INCLINED ____ DEG. FROM VERT.	15. ELEVATION GROUND WATER: none encountered
	16. DATE HOLE: STARTED 29Sept76 ; COMPLETED 30 Sept 76
7. THICKNESS OF OVERBURDEN: 36.0'	17. ELEVATION TOP OF HOLE: 468.0'
8. DEPTH DRILLED INTO ROCK: 33.0'	18. TOTAL CORE RECOVERY FOR BORING: 94 %
9. TOTAL DEPTH OF HOLE: 69.0'	19. SIGNATURE OF INSPECTOR: William E Hancock

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g	
	0		ML, red, clayey silt		1	W.T. 50'	12
			CL, red, lean clay with mica		2	Water table reading	
					3	24 hrs. after	33
					4	hole completed.	100
	5				5	W.T. 50'	100/0.9
					6	Date 29 Sept	100/.9'
					7	Depth to water	100/.9'
	10		SC, red, fine granular sand like saprolite.		8	during drilling by electric log	58
			ML, red, silt, powder saprolite, structureless		9		71
					10		64
					11		46
	15				12		60
			- green grey, structure ferromagnesiums		13		61
					14		100/.8'
	20		- green gray, structure biotite		15		100/1.
					16		100/.5'
					17		100/.6
	25		SC, white to pink granular clayey saprolite, pegmatite, qtz.& fldspr.		18		100/.6
					19		100/.5
			ML, green, structureless saprolite		20		100/.1
	30				21		100/.9

------------continued on page 2------------------------

NOTE: Soils field classified in accordance with the Unified Soil Classification System.

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE	Hole No. PB -7
PROJECT Design Earthquake and Hazard Study	INSTALLATION Richard B Russell Dam and Lake	SHEET 2 OF SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	30		ML, green saprolite, silt structureless		22	100/.1'
					23	100/.1'
	35				24	100/.1'
	36					scale change@ 36.0'
	39		FM 36.0' to 59.0' hole was advanced with rock bit and catch samples from drilling mud was used to check continunity in stratum			
	49					
	59			***		
	69		Biotite-hornblende-quartz-feldspar- gneiss, granitic cexture, slightly lineated with a number of high angle fractures. Pegmatite lens near bottom of hole	94	1	FM 59.0' To 69.0' Run 10.0' Rec 9.4' CL 0.6' RDQ 96%

bottom of hole

washed hole clean @ end of 48 hrs
w.t. stood at 50.0'

*** Sample sent to SAD Laborartoy for petrographic report

NOTE: Soils field classified in accordance with the Unified Soil Classification System.

Hole No. PB-8

DRILLING LOG	DIVISION SOUTH ATLANTIC	INSTALLATION RICHARD B RUSSELL DAM AND LAKE	SHEET 1 OF SHEETS

1. PROJECT Design Earthquake and Hazard Study	10. SIZE AND TYPE OF BIT splitspoon sampler & NX
2. LOCATION (Coordinates or Station) Patterson Branch Fault	11. DATUM FOR ELEVATION SHOWN (TBM or MSL) MSL
3. DRILLING AGENCY Savannah District	12. MANUFACTURER'S DESIGNATION OF DRILL 314 Failing
4. HOLE NO. (As shown on drawing title and file number) PB -8	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN — DISTURBED 0 — UNDISTURBED
5. NAME OF DRILLER B. Roundtree	14. TOTAL NUMBER CORE BOXES 1
6. DIRECTION OF HOLE XKXX VERTICAL ☐ INCLINED ______ DEG. FROM VERT.	15. ELEVATION GROUND WATER 405.0'
	16. DATE HOLE — STARTED 2 Oct.76 — COMPLETED 4 Oct.76
7. THICKNESS OF OVERBURDEN 31.0'	17. ELEVATION TOP OF HOLE 418.0
8. DEPTH DRILLED INTO ROCK 30.5'	18. TOTAL CORE RECOVERY FOR BORING %
9. TOTAL DEPTH OF HOLE 61.5'	19. SIGNATURE OF INSPECTOR William E. Hancock, Geologist

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0–30		SC, white, saprolite and degraded rock from dolerite dikes and pegmatite veins in a matrix of silt and sand			W.T. 13.0' Water table reading 24 hrs. after hole completed. none Date 2OCT. Depth to water during drilling

Recovery values (column g, from top to 30 ft): 100, 100, 100, 100, 100, 100, 95, 87, 100, 100, 100, 100, 100, 100, 100, 100, 100, 100, 100, 100

----continued on page 2----

NOTE: Soils field classified in accordance with Unified Soil Classification System.

DRILLING LOG (Cont Sheet) ELEVATION TOP OF HOLE

Hole No. PB-8

PROJECT: Design Earthquake and Hazard Study | INSTALLATION: RICHARD B RUSSELL DAM AND LAKE | SHEET 2 OF SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	30		scale change at 30.0'			
		X	augered out to 31.0'			
	35	?	Hornblende gneiss, salt and pepper color, vary saprolitic and altered in most of the recovered core.			Pull 1 FM 31.0' TO 41.0' Run 10.0' Rec 1.4' CL 8.6' Recovery 14 % RDQ 0
	40	? ?				Pull 2 FM 41.0' TO 49.9' Run 8.9' REC 1.0' CL 7.9' Recovery 11% RDQ 0
	45	?				
	50	X X		*** $\boxtimes$		Pull 3 FM 49.9' To 51.5' /lost due to bit malfunction /
	55 60	V V V V ...	Quartz- feldspar-hornblende gneiss, sound rock, granitic texture, and color.			Pull 4 FM 51.5' To 61.5' Run 10.0' Rec 8.4' CL 1.6' Recovery 84% RDQ 72
			Bottom of hole at 61.5 ' NOTE: Soils field classified in accordance with the Unified Soil Classification System.		*** Sample sent to GAD Lab for petrographic report	

Hole No. PB-9

DRILLING LOG	DIVISION South Atlantic	INSTALLATION Richard B Russell Dam & Lake	SHEET 1 OF 2 SHEETS

1. PROJECT Design Earthquake and Hazard Study	10. SIZE AND TYPE OF BIT splitspoon& NX
2. LOCATION (Coordinates or Station) Patterson Branch Fault	11. DATUM FOR ELEVATION SHOWN (TBM or MSL) MSL
3. DRILLING AGENCY Savannah District	12. MANUFACTURER'S DESIGNATION OF DRILL 314 Failing
4. HOLE NO. (As shown on drawing title and file number) PB-9	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN — DISTURBED 11 — UNDISTURBED
5. NAME OF DRILLER P. Roundtree	14. TOTAL NUMBER CORE BOXES 1
6. DIRECTION OF HOLE xxx VERTICAL ☐ INCLINED ___ DEG. FROM VERT.	15. ELEVATION GROUND WATER 321.2'
	16. DATE HOLE — STARTED 27 Sept 76 — COMPLETED 27 Sept 76
7. THICKNESS OF OVERBURDEN 22.5'	17. ELEVATION TOP OF HOLE 339.2
8. DEPTH DRILLED INTO ROCK 43.5'	18. TOTAL CORE RECOVERY FOR BORING %
9. TOTAL DEPTH OF HOLE 71.0'	19. SIGNATURE OF INSPECTOR Dan Waltz

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	0		ML, Brown to black silt w/ nodules of wad			W.T. 18.0' Date 27 Sept. 76 Depth to water during drilling
	5		CL, red to gray brown lean clayey sand			
	10		Ml, red silt with some sand and mica			W.T. 9.5 Water table reading 24 hrs. after hole completed.
	15		GC, gray brown, clayey gravel with sand. pebble size.			
			SC, gray brown, clayey sand			
			SP, brown, coarse grain sand			hole caved in to 10' moved over, cased to 19.5' and continued
	20		ML, lean silt, brown resembles saprolite			
	25		saprolite, quartz-feldspar biotite, hornblende gneiss			
	30		continued on page 2			

NOTE: Soils field classified in accordance with the Unified Soil Classification System.

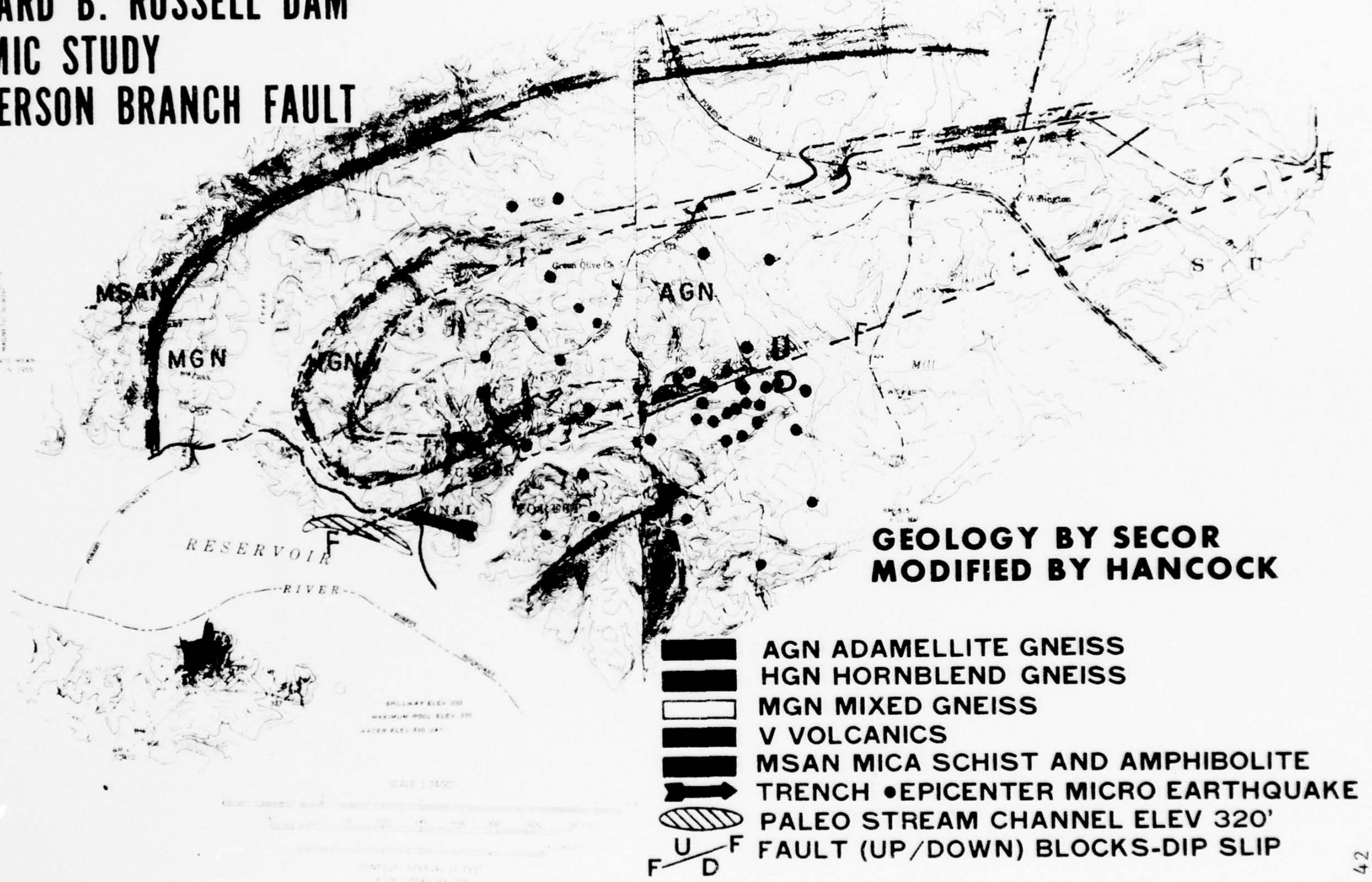
DRILLING LOG (Cont Sheet) | ELEVATION TOP OF HOLE | **Hole No.** PB -9

PROJECT Richard B Russell Dam and Lake | INSTALLATION Design Earthquake and Hazard Study | SHEET 2 OF SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	30		Drilled30.0' to 61.0' checked subsurface every 10' with drive.			
	40		Quartz-biotite-feldspar-hornblende gneiss			
	50		Quartz-biotite-feldspar-hornblende gneiss			
	60					
	70		Quartz-feldspar-biotite-hornblende gneiss, weathered badly.	20%	1	Pull 1 FM 61.0'-71.0' Run 10.0' Rec 2.0' loss 8.0'
			bottom of hole 71.0' NOTE: Soils field classified in accordance with the Unified Soil Classification System.			

ILLUSTRATIONS

RICHARD B. RUSSELL DAM
SEISMIC STUDY
PATTERSON BRANCH FAULT



D

C

B

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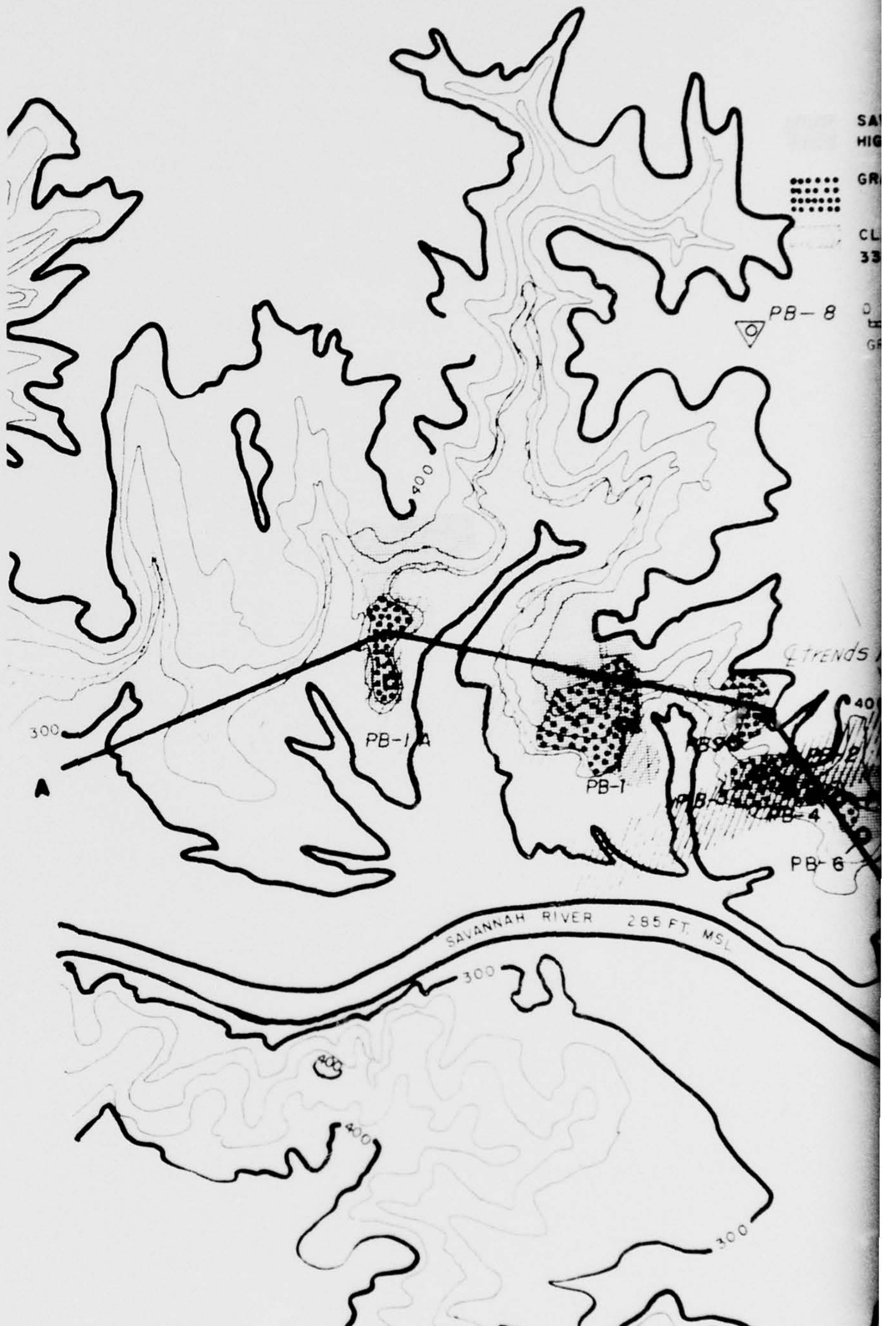
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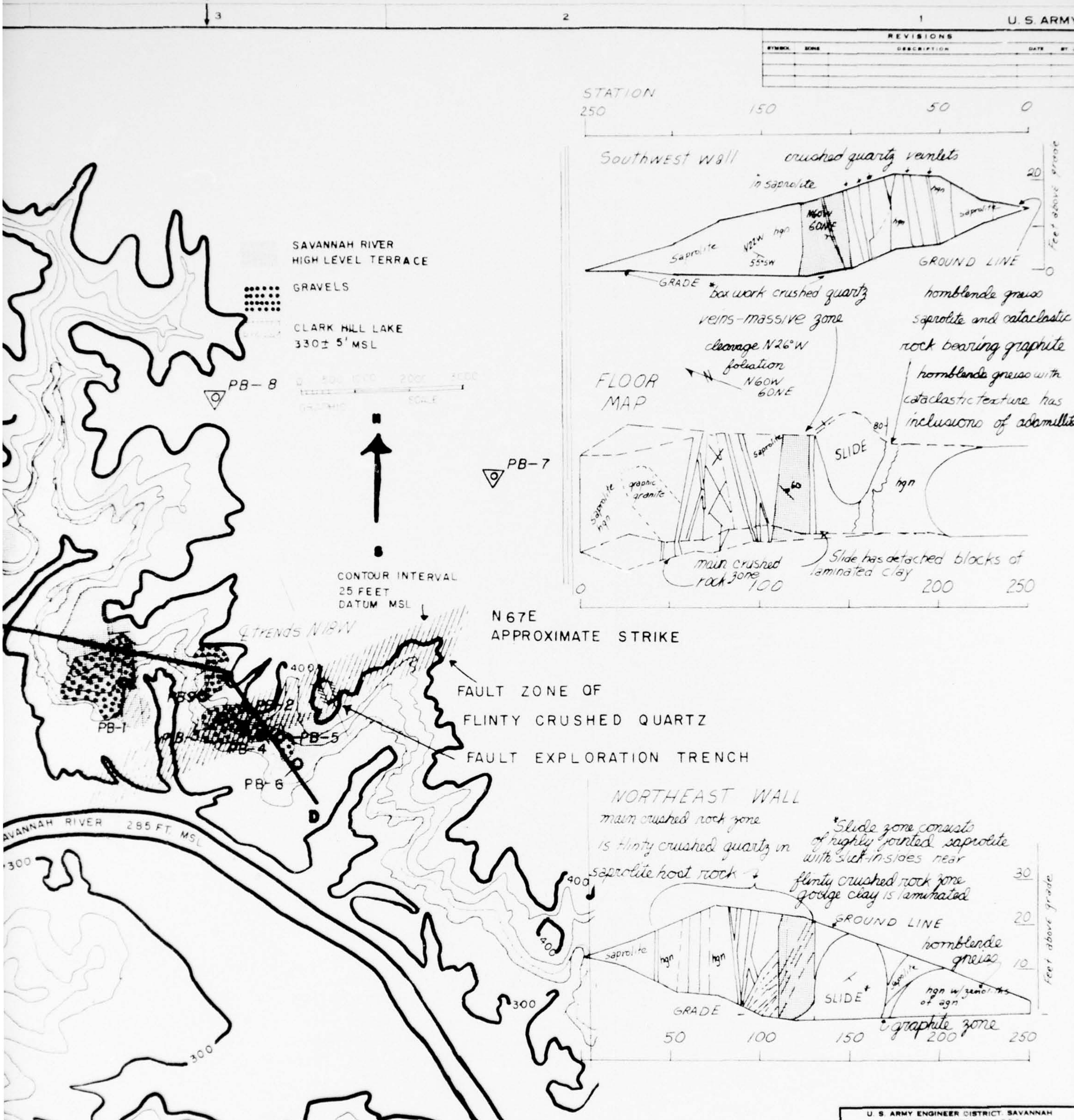
PB-1A
PB-1
PB-4
PB-6
SAVANNAH RIVER 285 FT. MSL
300
400
300



U. S. ARMY ENGINEER DISTRICT, SAVANNAH
CORPS OF ENGINEERS
SAVANNAH, GEORGIA

Patterson Branch Fault
Engineering Geology Map

SIZE	INVITATION NO.	FILE NO.	PLATE
F			
SCALE		SHEET	

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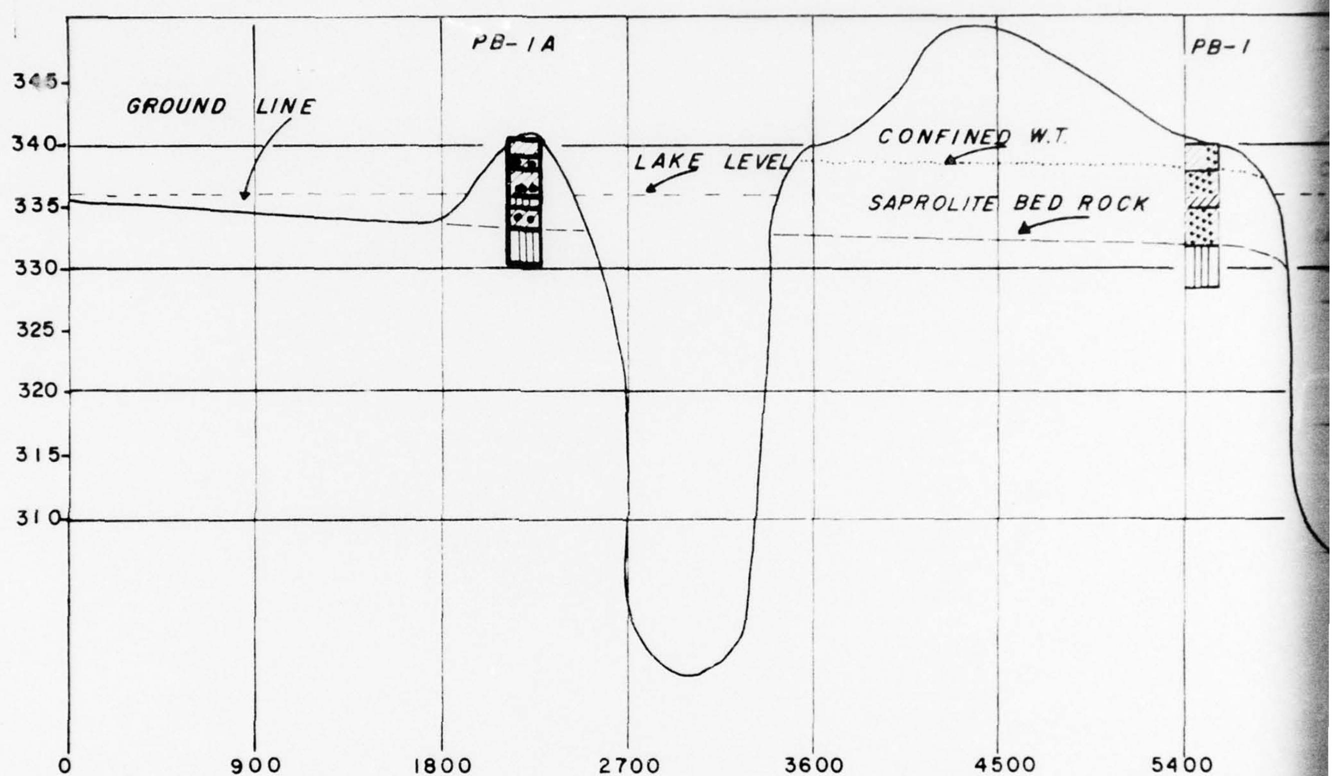
Section E

CORPS OF ENGINEERS

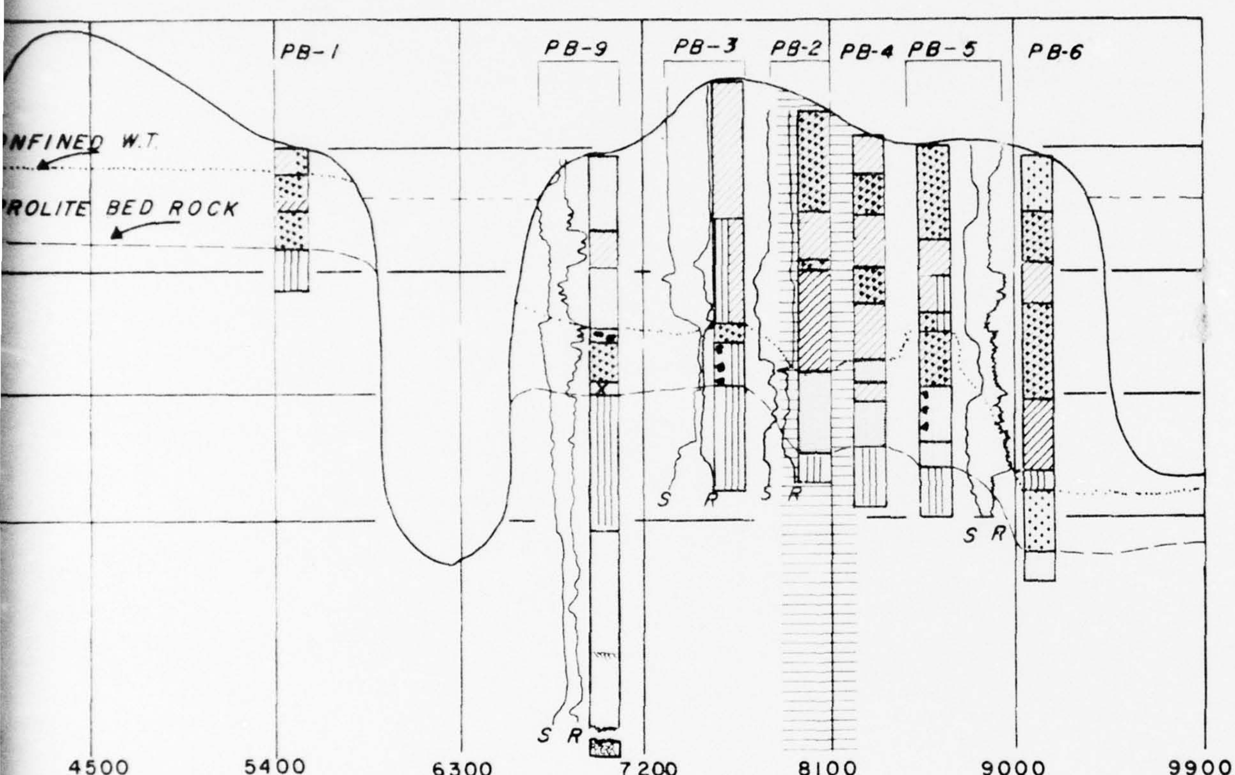


SECTION ALONG A–A'
GRID EAST OF A
SCALE IN FEET

U.S. ARMY

REVISIONS

SYMBOL	ZONE	DESCRIPTION	DATE	BY

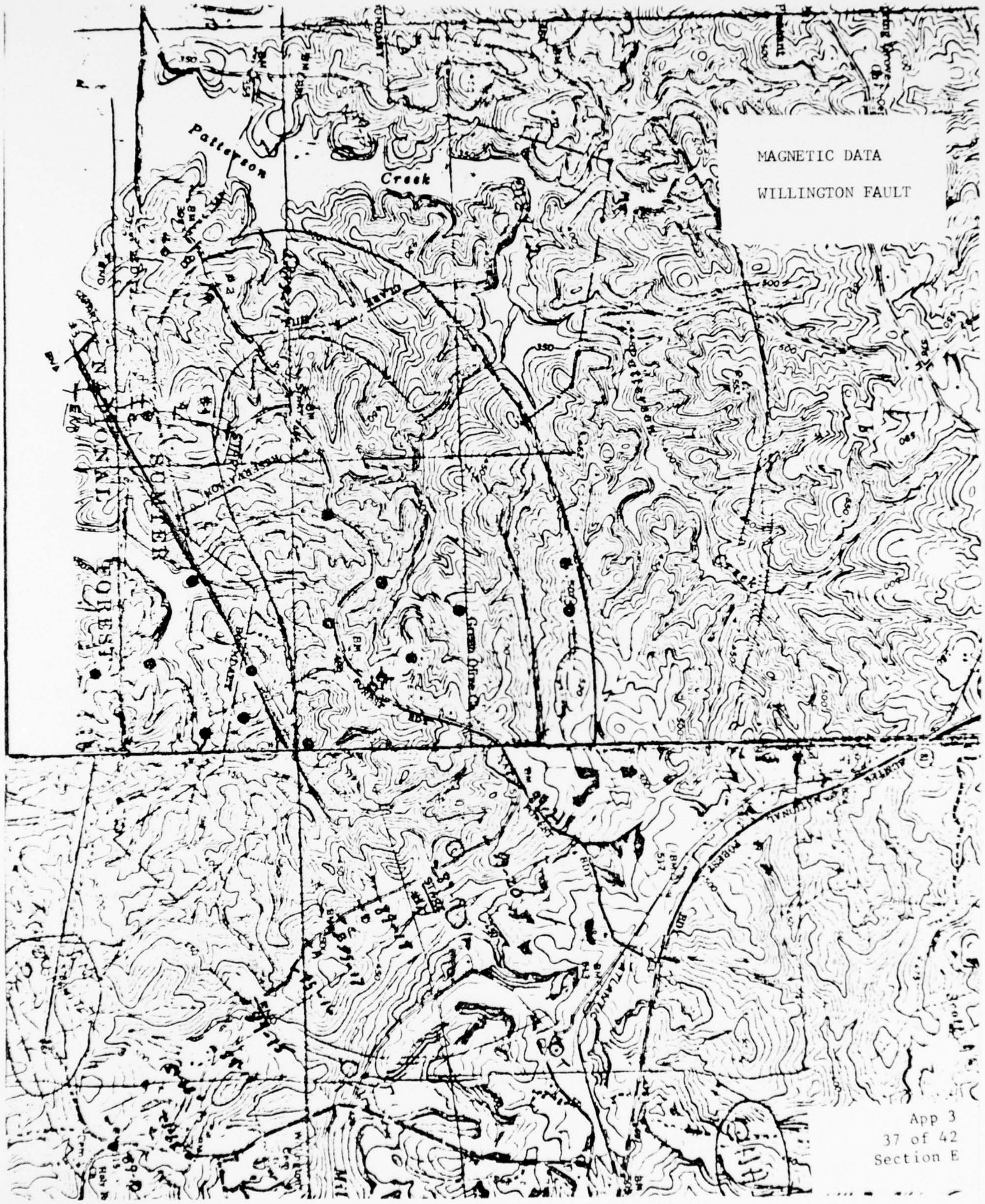


SECTION ALONG A—A'
GRID EAST OF A
SCALE IN FEET

U. S. ARMY ENGINEER DISTRICT, SAVANNAH
CORPS OF ENGINEERS
SAVANNAH, GEORGIA

PATTERSON BRANCH
FAULT
CROSS SECTION

SIZE	INVITATION NO.	FILE NO.	PLATE
F			
SCALE		SHEET	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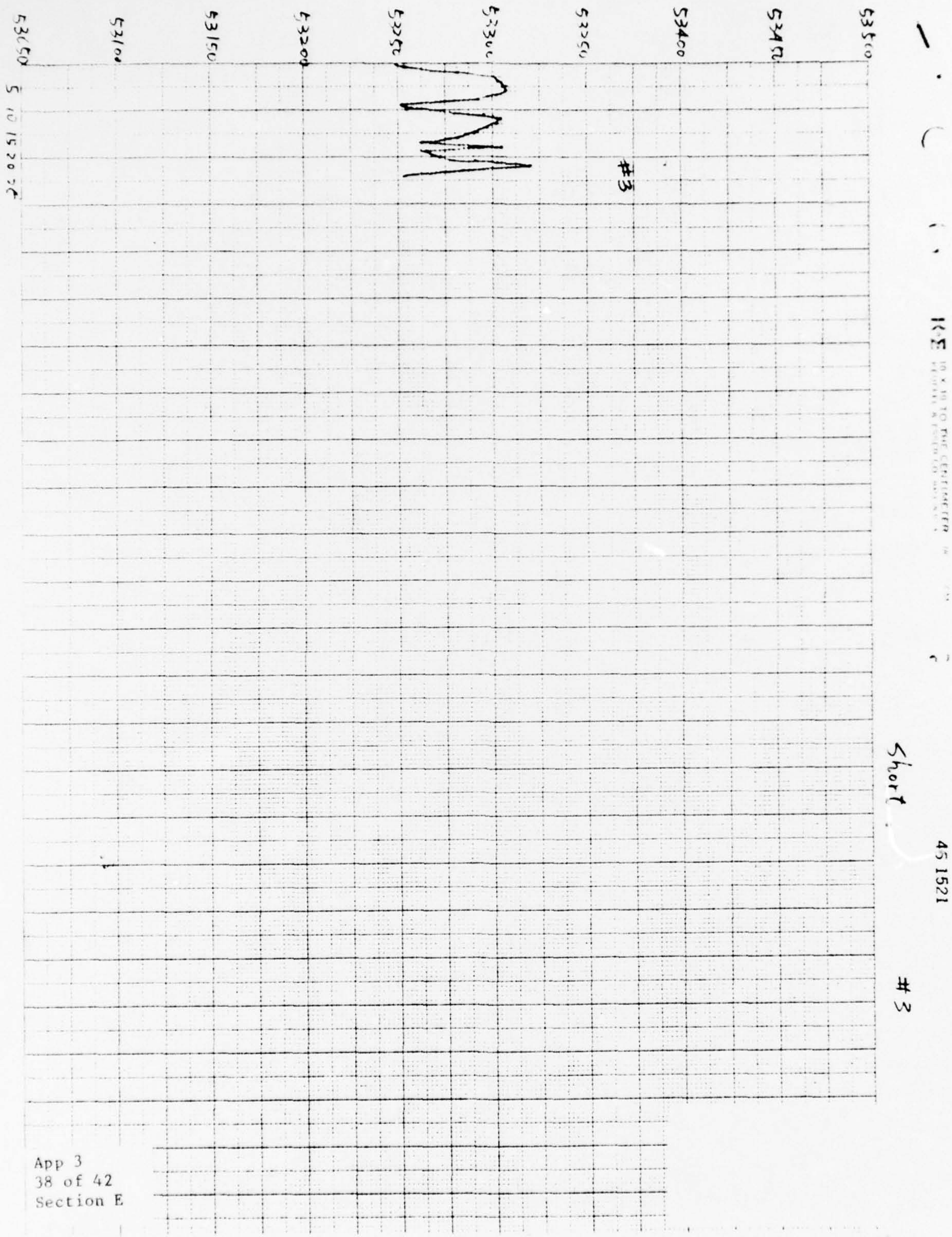
WILLINGTON FAULT
Patterson
Creek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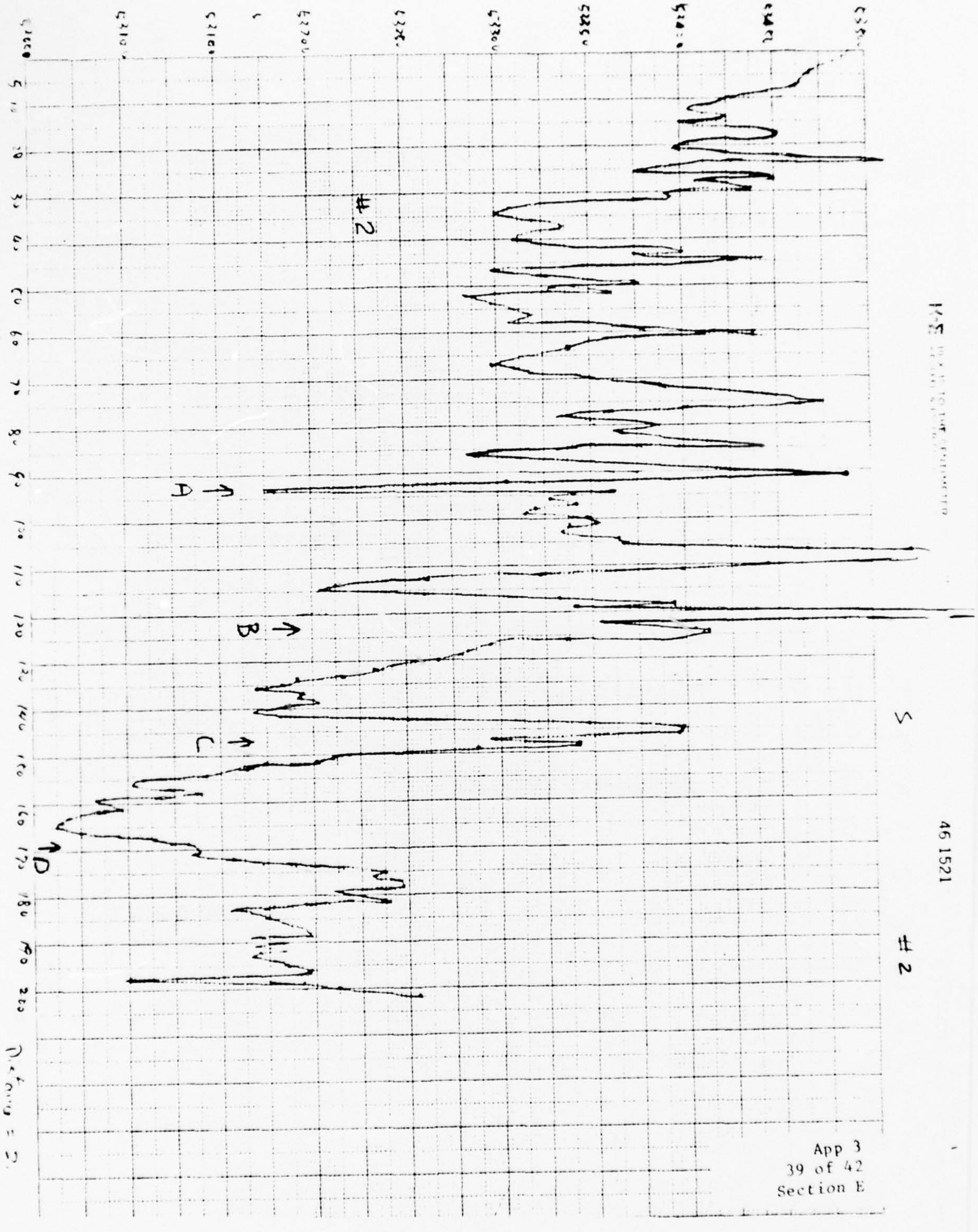

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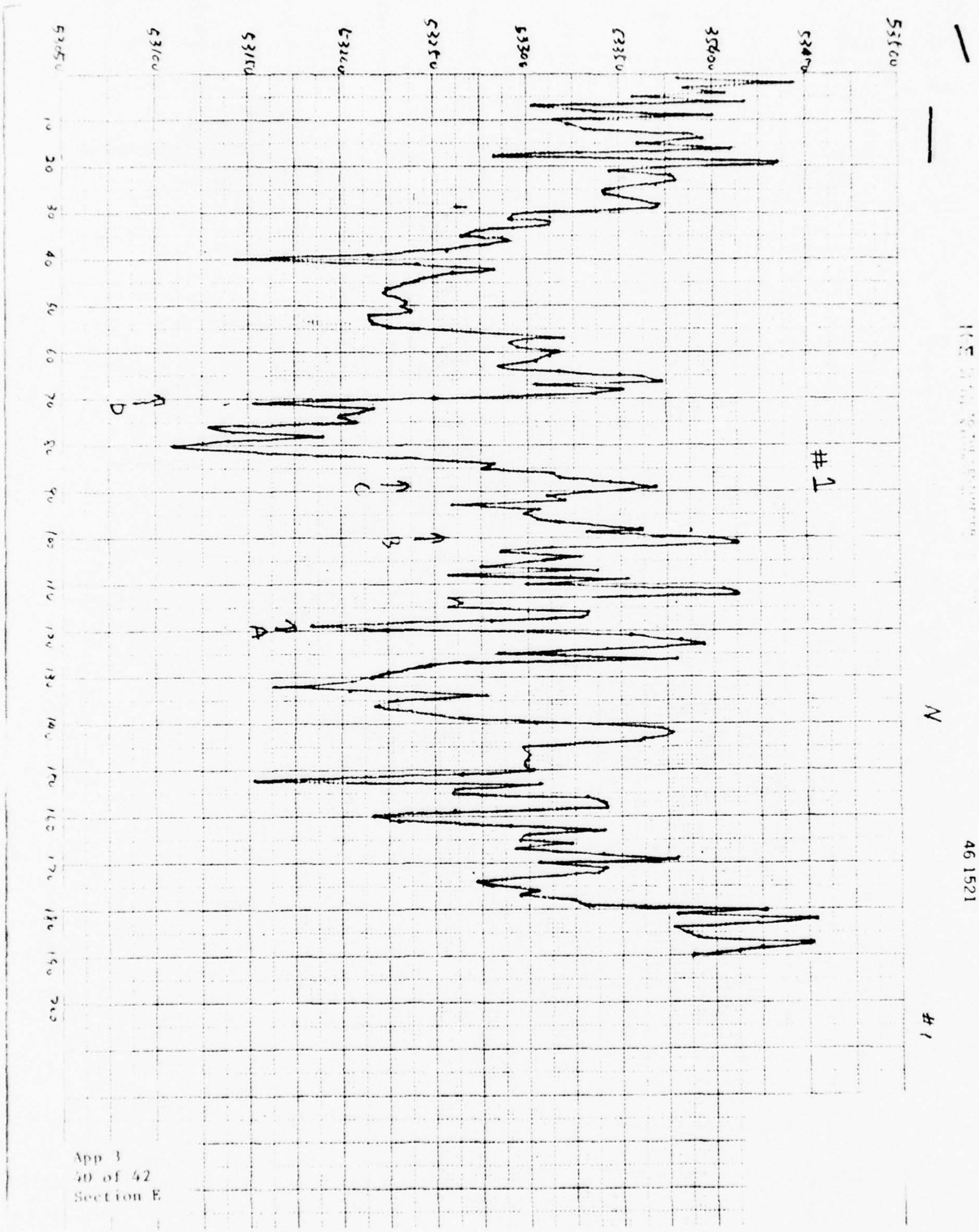
Section E



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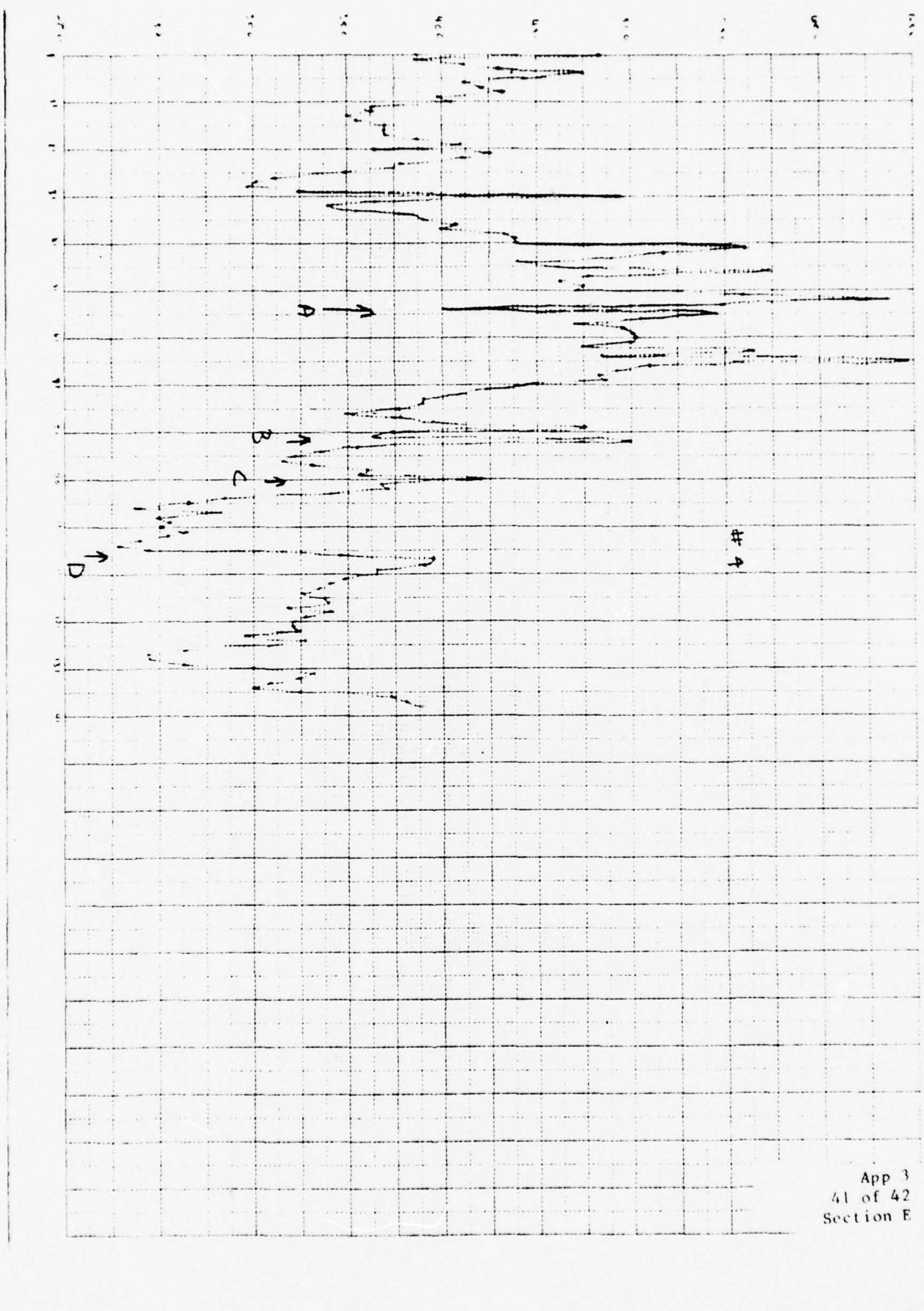
Section E



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SECTION F

BELAIR FAULT- SUPPORTION DOCUMENTATION

DEPARTMENT of the INTERIOR

news release

GEOLOGICAL SURVEY

Frank Forrester (703) 860-7444

For release: November 18, 1976

FAULT MOVEMENT IN GEORGIA NOT AS RECENT AS BELIEVED

New studies of the Belair fault zone near Augusta, Ga., indicate that movement along the fault may not have taken place within the last 2,500 years as previously concluded. Nevertheless, movement is known to have occurred sometime within the last 50 million years, the U.S. Geological Survey, Department of the Interior, said today.

The new data casts doubt on the significance of radiocarbon dates of organic matter in sediments cut by one of the faults in the Belair fault zone. It now appears that the dated material may have been contaminated by modern tree roots and that the enclosing sediments may not be as young as originally thought.

Recent studies -- including the detailed examination of a new trench 400 feet long and 15 feet deep dug across the fault zone this past October -- indicate that the organic matter which was dated in an earlier study (USGS Open File Report 75-680 announced by press release of January 12, 1976) did not give a reliable age on the last movement of the fault.

The importance of determining fault movements in parts of the eastern United States was emphasized by Dr. Henry Coulter, USGS Assistant Director for Environmental Conservation at the Survey's National Center, Reston, Va.

"Recent movement along such faults," Coulter said, "would have significant scientific and engineering implications. It is important to identify and determine the geographic distribution of geologic processes that might affect the safe siting of nuclear power reactors and other large engineered structures.

"The findings earlier this year indicating recent movement along the Belair fault zone were most unusual," Coulter said, "because most fault movements in the southeastern United States are believed to be older than 180 million years. The new studies cast doubt on the evidence for very recent movement."

(more)

Coulter said that studies of the Belair fault zone are still continuing in efforts to bracket more closely the age of the last movement along the fault zone. "At present," he said, "we can only conclude that the fault moved sometime after the Eocene (about 50 million years ago).

."This new evidence," Coulter said, "emphasizes the need to better understand the tectonic framework and relationships in the eastern United States, and to try to determine if such faulting occurred as distinct seismic events or as slow, continuous movement. No clearcut relationship between faulting and earthquakes has been determined in the eastern States such as has been established in California and other western States."

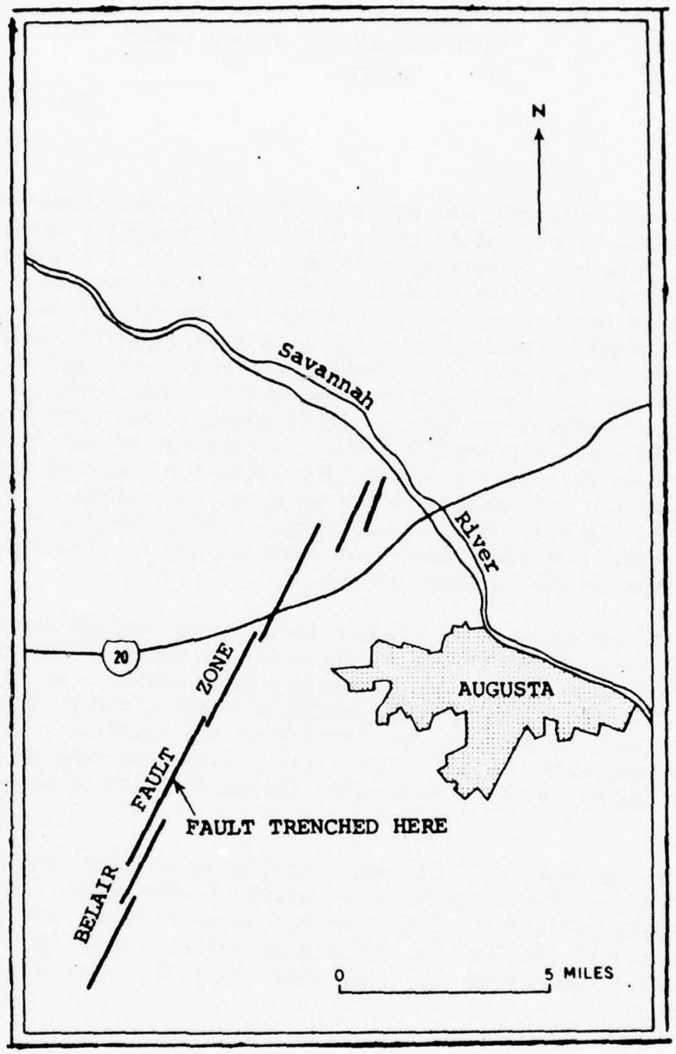
Coulter said that additional geologic mapping and investigations are continuing throughout the area surrounding the Belair fault zone. Current efforts, he said, involve a variety of techniques, including structural analysis, magnetostratigraphy, and detailed analysis of soils, to determine the age of the oldest undisturbed material resting on the fault.

Coulter said the USGS plans to release a detailed map of the wall of the October trench in the near future. The map will show relative positions of the faults, Piedmont rocks, Coastal Plain sediments, and the overlying sediments and soils as they were mapped in the trench wall.

Studies of the Belair fault zone are part of the U.S. Geological Survey's Reactor Hazards Research Program, aimed at obtaining data that will be helpful to the public and government agencies involved in making decisions concerning the design, siting, and construction of large structures.

# # # #

(See attached map showing location of Belair fault zone.)


N
Savannah
River
20
AUGUSTA
BELAIR FAULT ZONE
FAULT TRENCHED HERE
0
5 MILES

INT: 669-76

~~Ch, Geol~~ [illegible]

Ch, F&M [illegible]

F&M File

EN-FG

XX THRU EN-F

Fort Gordon, GA, Belair Fault

EN-FG

4 Mar 76

Mr. Titcomb/dmm/311

TO EN

1. In 1974, Bruce O'Connor, who was then of the Georgia State Geological Survey, discovered a fault in the Belair shale pit of the Georgia Vitrified Brick and Clay Company. This pit is located adjacent to Gate No. 1 (McKenna Gate) of Fort Gordon. Since that time, the U. S. Geological Survey, in cooperation with the Georgia State Survey, has begun an extensive investigation, including borings taken on Fort Gordon. The studies which they have completed indicate movement along this fault in the last 2,500 years and possibly as much as 9' of movement in the last 500 years. The fault does not occur as one straight plane but consists of offsets and a series of en echelon fault planes. For this reason it has not been possible to precisely predict the exact location of the fault in any area which has not been extensively investigated (see the attached letter). However, the fault reportedly does extend either under or very close to the new Eisenhower Hospital. It is the opinion of the principal USGS investigator, Dr. David Prowell, that the fault does not trend under the hospital but is slightly west of the hospital as shown on the attached sketch.

2. In light of the above it is planned to carry several of the borings to be made for the Fort Gordon Regional Dental Clinic (now proposed to be located southwest of the hospital) much deeper than we would have normally. In addition, I recommend that if funds can be made available (approximately $9,000), several deep borings should be made in the vicinity of the hospital. We should also continue to cooperate with Doctors Prowell and O'Connor so that we may have access to their most recent opinions concerning the possibility of movement along the fault.

3. This, in my opinion, is a minimum that the District should do to be on top of the latest thinking of the researchers working in the area. There have been a rash of newspaper articles recently concerning earthquakes and faults in the Clark Hill Reservoir area and we may be questioned concerning this Belair Fault and the possibility of danger to the Eisenhower Hospital. This will aid us in having our reply ready.

2 Incl
as

ROBERT G. STANSFIELD
Acting, Chief, Geology Section

CF:
EN-MA, Attn: Mr. McKenzie

United States Department of the Interior

GEOLOGICAL SURVEY
RESTON, VIRGINIA 22092

Stop 926
February 18, 1976

Earl Titcombe
Savannah District Corps of Engineers
P. O. Box 889
Savannah, Georgia 31402

Dear Earl:

I am writing you in response to a call I got from Bruce O'Connor concerning the location of the Belair Fault on Fort Gordon in Augusta. Since the U.S.G.S. did most of the drilling, I am answering your request.

The enclosed map is a composite of the Grovetown and Augusta West 7.5 minute topographic maps showing the locations of strategic drill holes. The red numbers represent the elevation (above sea level) of the Piedmont-Coastal Plain unconformity. This should enable you to approximate the elevation of the unconformity in the area of your test drilling. The vertical displacement on the fault north of the golf course should be about 45 to 50 feet. I do not think that you will have any difficulty in determining whether you are on the up or down side. You may, however, find it difficult to determine where the fault cuts the surface without extensive investigation. I have drawn a dashed yellow line on the map to indicate where I think the fault is located assuming it is a straight single shear. I urge that you use caution in determining the specific location of the fault from our data.

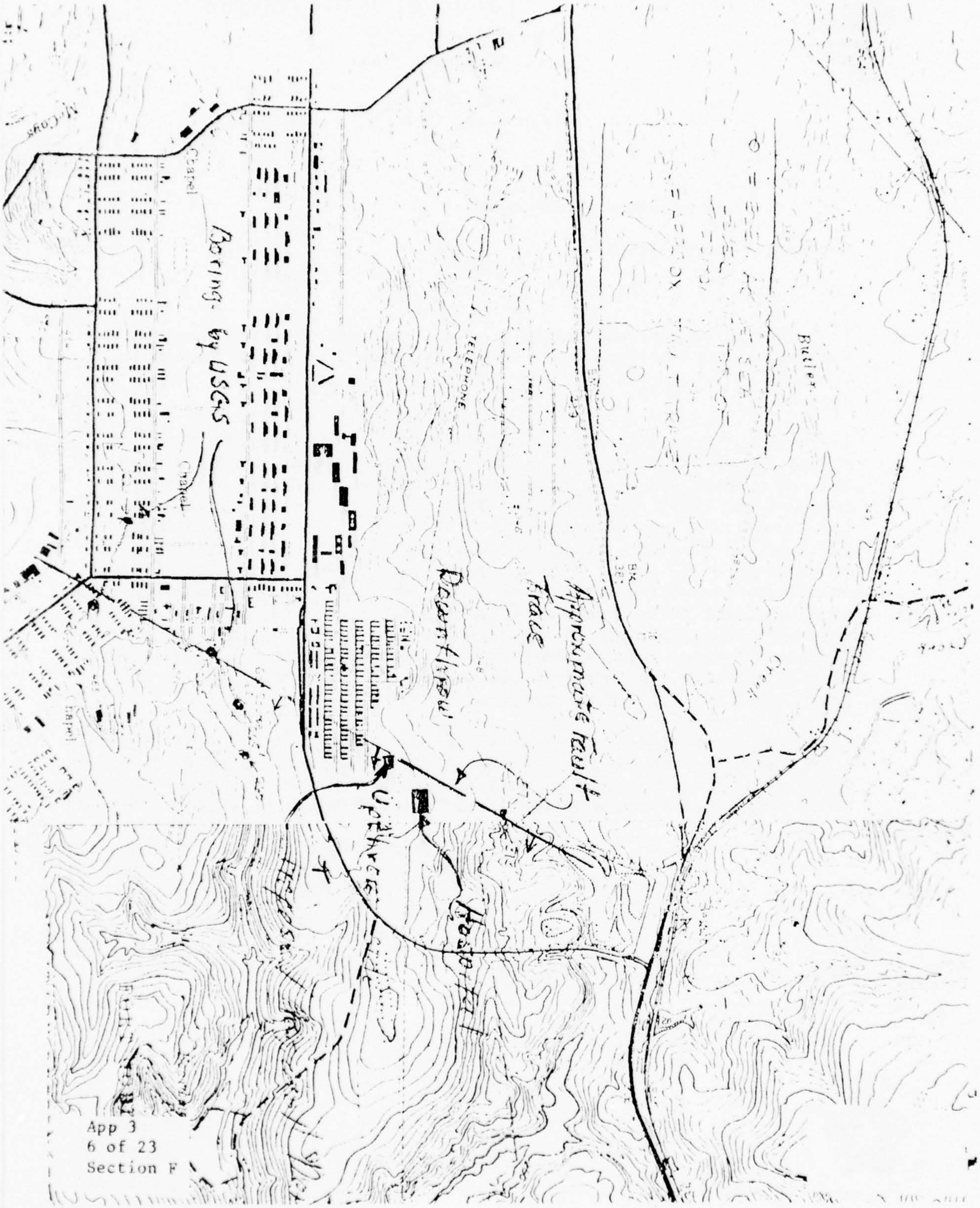
I am very interested in the results of your drilling and I would appreciate having copies of the well logs. Also, any material that you recover which might contain spores or pollen, we would like to analyze. If I can be of further assistance to you, feel free to contact me at 703-860-6462.

Yours truly,

David Prowell

Encl.

AMERICAN REVOLUTION BICENTENNIAL 1776-1976


Boring by USGS
Chapel
TELEPHONE
Approximate fault trace
Downthrown
Upthrown
Hospital
Butler

Hole No. CS-3

DRILLING LOG	DIVISION SOUTH ATLANTIC	INSTALLATION FT. GORDON, GA.	SHEET 1 OF 9 SHEETS

1. PROJECT: DENTAL CLINIC
2. LOCATION (Coordinates or Station):
3. DRILLING AGENCY: SAVANNAH DISTRICT
4. HOLE NO. (As shown on drawing title and file number): CS-3
5. NAME OF DRILLER: T. SCOTT
6. DIRECTION OF HOLE: [X] VERTICAL [ ] INCLINED ____ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN: 241.8'
8. DEPTH DRILLED INTO ROCK: 41.2'
9. TOTAL DEPTH OF HOLE: 283.0'
10. SIZE AND TYPE OF BIT: 1 3/8" ID SPLITSPOON + 4 x 5 CORE BBL.
11. DATUM FOR ELEVATION SHOWN (TBM or MSL): TBM
12. MANUFACTURER'S DESIGNATION OF DRILL: FAILING 314
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED 10; UNDISTURBED 0
14. TOTAL NUMBER CORE BOXES: 28
15. ELEVATION GROUND WATER:
16. DATE HOLE: STARTED 22 JULY 1976; COMPLETED 12 AUGUST 1976
17. ELEVATION TOP OF HOLE: 478.4
18. TOTAL CORE RECOVERY FOR BORING: 88 %
19. SIGNATURE OF INSPECTOR: BELVILLE

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	~~% CORE RECOVERY~~ % ← moisture Content	BOX OR SAMPLE NO. JAR	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g	BLOWS
	0		SM-DARK BROWN, SILTY FINE SAND		1		28
			SP-LIGHT BROWN, POORLY GRADED SAND	4.0	2	W.T. 25.0' Date 22 JUL. 76 Depth to water during drilling	30, 14
	5		SM-RED, SILTY, FINE TO MEDIUM SAND		3	W.T. 24.0' Water table reading 24 hrs. after hole completed.	12, 13
					4		15
	10						20, 20
				7.2	5		19
	15						18, 30, 60
			RED AND WHITE	7.4	6		40
	20						38
			RED				38
			SP-RED AND WHITE, POORLY GRADED SAND		7		29
	25						19, 18
			SM-RED, SILTY, FINE TO MEDIUM SAND	12.5	8		35, 36
	30		CONTINUED ON SHEET #2				

NOTE: Soils field classified in accordance with the Unified Soil Classification System.

BLOWS PER FOOT: Number required to drive $1\frac{3}{8}$" ID splitspoon w/140 lb. hammer falling 30".

DRILLING LOG (Cont Sheet) | ELEVATION TOP OF HOLE: 478.4 | **Hole No.** CS-3

PROJECT: DENTAL CLINIC | INSTALLATION: FT. GORDON, GA. | SHEET 2 OF 9 SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g	BLOWS
	30		SP-ORANGE, POORLY GRADED SAND		9		33
							41
							40
	35		CL-MOTTLED RED AND WHITE, KAOLIN CLAY, SOFT AND CHACKY WHEN DRY		10	NOTE: BEGAN CORING 36.0'	40
				87	Box 1	PULL #1 36.0' TO 39.0' RUN 3.0' REC 2.6' CL 0.4'	
	40			73		PULL #2 39.0' TO 44.5' RUN 5.5' REC 4.0' CL 1.5'	
	45			60	Box 2	PULL #3 44.5' TO 48.0' RUN 3.5' REC 2.1' CL 1.4'	
			RED, WHITE, PURPLE, MICACEOUS				
	50		WHITE, MICACEOUS	84		PULL #4 48.0' TO 53.0' RUN 5.0' REC 4.2' CL . '	
			PURPLE, MICACEOUS, SOME FINE SAND				
	55		ORANGE + WHITE, FINE SAND, MICACEOUS	76	Box 3	PULL #5 53.0' TO 58.0' RUN 5.0' REC 3.8' CL 1.2'	
			SM-LIGHT GRAY, MEDIUM TO COARSE, SILTY, MICACEOUS SAND				
	60		ORANGE	76		PULL #6 58.0' TO 63.0' RUN 5.0' REC 3.6' CL 1.4'	
			LIGHT GRAY				
	65		CL-WHITE WITH ORANGE MOTTLING, KAOLIN CLAY	90	Box 4	PULL #7 63.0' TO 68.0' RUN 5.0' REC 4.5' CL 0.5'	
				78		PULL #8 CONTINUED 68.0' TO 73.0'	
	70						

CONTINUED ON SHEET #3

DRILLING LOG (Cont Sheet) | ELEVATION TOP OF HOLE: 478.4 | **Hole No.** CS-3

PROJECT: DENTAL CLINIC | INSTALLATION: FT. GORDON, GA. | SHEET 3 OF 9 SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	70		CL-WHITE WITH ORANGE MOTTLING, KAOLIN CLAY			RUN 5.0' REC 3.9' CL 1.1'
	75			88	BOX 5	PULL #9 73.0' TO 78.0' RUN 5.0' REC 4.4' CL 0.6'
			LIGHT BROWN			
	80		GRAY WITH ORANGE MOTTLING, SOME FINE SAND	100	BOX 6	PULL #10 78.0' TO 83.0' RUN 5.0' REC 5.5' CG 0.5'
	85		SM-LIGHT GRAY, MEDIUM TO COARSE, MICACEOUS SILTY SAND, ANGULAR	88		PULL #11 83.0' TO 88.0' RUN 5.0' REC 4.4' CL 0.6'
	90		CL-GRAY WITH RED MOTTLING, WITH MEDIUM TO COARSE SAND	92	BOX 7	PULL #12 88.0' TO 93.0' RUN 5.0' REC 4.6' CL 0.4'
			GRAY, LENSES OF COARSE QUARTZ SAND			
	95		SM-GRAY, MOTTLED ORANGE SAND, MICACEOUS, SILTY, MEDIUM, INTERLAYERED WITH COARSE SANDS AND GRAVELS AND CL KAOLIN CLAY	36		PULL #13 93.0' TO 98.0' RUN 5.0' REC 1.8' CL 3.2'
	100		CL-WHITE, MICACEOUS, KAOLIN, CLAY	78	BOX 8	PULL #14 98.0' TO 101.5' RUN 3.5' REC 2.7' CL 0.8'
	105		SM-GRAY, FINE TO MEDIUM, SILTY SAND, WITH SOME GRAVELS AND COARSE SANDS, VERY MICACEOUS, TRACE OF HEAVY MINERALS, SOME ORGANICS	76		PULL #15 101.5' TO 106.5' RUN 5.0' REC 3.8' CL 1.2'
				100	BOX 9	PULL #16 106.5' TO 111.5' RUN 5.0' REC 5.4' CG 0.4'
	110		CONTINUED ON SHEET #4			

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE 478.4	Hole No. CS-3
PROJECT DENTAL CLINIC	INSTALLATION FT. GORDON, GA.	SHEET 4 OF 9 SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	110		SM - GRAY,			PULL #16 CONTINUED
			FINE TO MEDIUM, SILTY SAND, WITH SOME GRAVELS AND COARSE SANDS,	76	BOX 9	PULL #17 111.5' TO 116.5' RUN 5.0' REC 3.8' CL 1.2'
	115		VERY MICACEOUS, TRACE OF HEAVY MINERALS, SOME ORGANICS			
	120			80	BOX 10	PULL #18 116.5' TO 121.5' RUN 5.0' REC 4.0' CL 1.0'
	125			96		PULL #19 121.5' TO 126.5' RUN 5.0' REC 4.8' CL 0.2'
	130			24	BOX 11	PULL #20 126.5' TO 131.5' RUN 5.0' REC 1.2' CL 3.8'
			ML - LIGHT BROWN			
	135		SM - GRAY, FINE TO MEDIUM. SILTY, MICACEOUS, SAND	94		PULL #21 131.5' TO 136.5' RUN 5.0' REC 4.7' CL 0.3'
	140		BLACK TO DARK BROWN, ORGANIC SILTS, FINE TO MEDIUM SANDS, ROOTS AND WOOD CHIPS, INTERBEDDED CONTACT WITH UNDERLYING SAND (CARBON DATE SAMPLE)	46	BOX 12	PULL #22 136.5' TO 141.5' RUN 5.0' REC 2.3' CL 2.7'
	145		LIGHT GRAY, FINE TO MEDIUM, SILTY MICACEOUS	68		PULL #23 141.5' TO 146.5' RUN 5.0' REC 3.4' CL 1.6'
			147.2' - 151.5' SOME ORANGE STREAKS	90	BOX 13	PULL #24 146.5' TO 151.5' RUN 5.0' REC 4.5' CL 0.5'
	150		CONTINUED ON SHEET #5			

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE 478.4	Hole No. CS-3
PROJECT DENTAL CLINIC	INSTALLATION FT. GORDON, GA.	SHEET 5 OF 9 SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	150		SM- LIGHT GRAY, MICACEOUS, FINE TO MEDIUM, SILTY 147.2' - 151.5' SOME ORANGE STREAKS			PULL #24 CONTINUED
			CL- LIGHT GRAY TO LIGHT BROWN, WITH ORANGE STREAKS, KAOLIN CLAY	90	BOX 13	PULL #25 151.5' TO 156.5' RUN 5.0' REC 4.5' CL 0.5'
	155		MH- LIGHT BROWN, SOFT, WET SILT	60		PULL #26 156.5' TO 161.5' RUN 5.0' REC 3.0' CL 2.0'
	160		SM- LIGHT GRAY, FINE TO MEDIUM GRAINED, SILTY, MICACEOUS, SAND, SOME KAOLIN CLAY BALLS UP TO 1/2" DIAMETER		BOX 14	
	165			100		PULL #27 161.5' TO 166.5' RUN 5.0' REC 5.6' CG 0.6'
	170			100	BOX 15	PULL #28 166.5' TO 171.5' RUN 5.0' REC 5.5' CG 0.5'
	175			92	BOX 16	PULL #29 171.5' TO 176.5' RUN 5.0' REC 4.6' CL 0.4'
			FINE GRAVEL + VERY COARSE SAND			
	180		CL- GRAY, MOTTLED YELLOW, HARD INTERVAL 179.2'-179.3' PURPLE UNDERLAIN BY WHITE 30° JOINT	100		PULL #30 176.5' TO 181.5' RUN 5.0' REC 5.2' CG 0.2'
	185		DARK RED, SOME ORANGE AND WHITE MOTTLING	26	BOX 17	PULL #31 181.5' TO 186.5' RUN 5.0' REC 1.3' CL 3.7'
			CH- BROWN & WHITE, KAOLIN CLAY WITH COARSE QUARTZ SAND			
			CL- ORANGE, KAOLIN CLAY, MICACEOUS WITH MEDIUM TO COARSE QUARTZ SAND	62		PULL #32 186.5' TO 191.5' RUN 5.0' REC 3.1' CL 1.9'
	190		PURPLE AND WHITE			

CONTINUED ON SHEET #6

DRILLING LOG (Cont Sheet) | ELEVATION TOP OF HOLE: 478.4 | **Hole No.** CS-3

PROJECT: DENTAL CLINIC | INSTALLATION: FT. GORDON, GA. | SHEET 6 OF 9 SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	190		CL - PURPLE & WHITE CONTINUED			PULL #32 CONTINUED
	195		SM- LIGHT GRAY TO LIGHT PURPLE, MEDIUM TO FINE GRAINED, SILTY, MICACEOUS SAND, LENSES OF CH	92	BOX 18	PULL #33 191.5' TO 196.5' RUN 5.0' REC 4.6' CL 0.4'
	200		LIGHT GRAY MOTTLED ORANGE, MICACEOUS, SAND, INTERBEDDED WITH BLUE QUARTZ GRAVELS UP TO 1 1/2" DIAMETER	90		PULL #34 196.5' TO 201.5' RUN 5.0' REC 4.5' CL 0.5'
	205		LIGHT GRAY, SOME 1 1/2" DIAMETER QUARTZ GRAVELS	98	BOX 19	PULL #35 201.5' TO 206.5' RUN 5.0' REC 4.9' CL 0.1'
	210		IRON STAINED	22		PULL #36 206.5' TO 211.5' RUN 5.0' REC 1.1' CL 3.9'
	215		THIN ORANGE SM LAYERS AT INTERVALS: 211.5' TO 211.9' 212.7' TO 213.0' 213.7' TO 213.9' 219.4' TO 219.5'	88	BOX 20	PULL #37 211.5' TO 216.5' RUN 5.0' REC 4.4' CL 0.6'
	220			100		PULL #38 216.5' TO 221.5' RUN 5.0' REC 5.0'
	225			44	BOX 21	PULL #39 221.5' TO 226.5' RUN 5.0' REC 2.2' CL 2.8'
	230		THIN CLAY LENSE AT 227.3'	42		PULL #40 226.5' TO 231.5' RUN 5.0' REC 2.1' CL 2.9'

CONTINUED ON SHEET #7

DRILLING LOG (Cont Sheet)

ELEVATION TOP OF HOLE: 478.4

Hole No. CS-3

PROJECT: DENTAL CLINIC

INSTALLATION: FT. GORDON, GA.

SHEET 7 OF 9 SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	230		SM - LIGHT GRAY, SOME 1 1/2" DIAMETER QUARTZ GRAVELS			PULL #40 CONTINUED
	235			88		PULL #41 231.5' TO 236.5' RUN 5.0' REC 4.4' CL 0.6'
	240		ROUNDED QUARTZ GRAVELS TOP OF ROCK 241.8'	56	BOX 22	PULL #42 236.5' TO 241.5' RUN 5.0' REC 2.8' CL 2.2' NOTE: SCALE CHANGE AT 240.0'
	242		GNEISS - MOTTLED, CREAMY WHITE, Fe STAINED, VERY SOFT, BADLY WEATHERED, HIGHLY ALTERED, FOLIATED, VERY MICACEOUS	38	BOX 23	PULL #43 241.5' TO 246.5' RUN 5.0' REC 3.1' CL 1.9'
	244					
	246		BROWN + GREEN, Fe STAINED, WELL JOINTED	100		PULL #44 246.5' TO 251.5' RUN 5.0' REC 5.0'
	248					
	250					
	252		CONTINUED ON SHEET #8			PULL #45 CONTINUED

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE 478.4	Hole No. CS-3
PROJECT DENTAL CLINIC	INSTALLATION FT. GORDON, GA.	SHEET 8 OF 9 SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	252		GNEISS - BROWN + GREEN, FE STAINED, WELL JOINTED			PULL #45 CONTINUED 251.5' TO 256.5' RUN 5.0' REC 4.0' CL 1.0'
	254			80		
	256					PULL #46 256.5' TO 261.5' RUN 5.0' REC 4.3' CL 0.7'
	258		258.5' JOINT 80°	86		
	260		259.6' JOINT 50°			
			260.6' JOINT 70°			
			MOTTLED RED, GREEN, BROWN, BLUE, WELL JOINTED			
	262					PULL #47 261.5' TO 266.5' RUN 5.0' REC 4.9' CL 0.1'
			262.7' JOINT 50°			
	264			98		
	266		266.9' SLICKENSIDED JOINT 45°			PULL #48 266.5' TO 271.5' RUN 5.0' REC 4.9' CL 0.1'
			267.6' " " 55°			
			268.6' " " 60°			
	268		CONTINUED ON SHEET #9			

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE 478.4	Hole No. CS-3
PROJECT DENTAL CLINIC	INSTALLATION FT GORDON, GA.	SHEET 9 OF 9 SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	268		GNEISS - MOTTLED RED, GREEN, BROWN, BLUE, WELL JOINTED	98		PULL # 48 CONTINUED
	270					
	272		272.5' FAULT GOUGE	100		PULL #49 271.5' TO 274.0' RUN 2.5' REC 2.5'
	274		QUARTZ LENSE	76	BOX 27	PULL #50 274.0' TO 279.0' RUN 5.0' REC 3.8' CL 1.2'
	276		GNEISS - GREEN, MODERATELY HARD, UNWEATHERED, GNEISSIC STRUCTURES, 45° FOLIATION, FINE GRAINED			
	278					
	280			82	BOX 28	PULL #51 279.0' TO 283.0' RUN 4.0' REC 3.3' CL 0.7'
	282					
	283		BOTTOM OF HOLE 283.0'			

Hole No. CS-2

DRILLING LOG	DIVISION: SOUTH ATLANTIC	INSTALLATION: FT. GORDON, GA.	SHEET 1 OF 8 SHEETS

1. PROJECT: DENTAL CLINIC	10. SIZE AND TYPE OF BIT: 4 X 5 CORE BARREL
2. LOCATION (Coordinates or Station)	11. DATUM FOR ELEVATION SHOWN (TBM or MSL): TBM
3. DRILLING AGENCY: SAVANNAH DISTRICT	12. MANUFACTURER'S DESIGNATION OF DRILL: CD-28
4. HOLE NO. (As shown on drawing title and file number): CS-2	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED 12; UNDISTURBED 0
5. NAME OF DRILLER: W. MACILWAIN	14. TOTAL NUMBER CORE BOXES: 27
6. DIRECTION OF HOLE: [X] VERTICAL [ ] INCLINED ____ DEG. FROM VERT.	15. ELEVATION GROUND WATER: 454.5
	16. DATE HOLE: STARTED 12 AUGUST 1976; COMPLETED 25 AUGUST 1976
7. THICKNESS OF OVERBURDEN: 249.2'	17. ELEVATION TOP OF HOLE: 478.1
8. DEPTH DRILLED INTO ROCK: 14.2'	18. TOTAL CORE RECOVERY FOR BORING: 82 %
9. TOTAL DEPTH OF HOLE: 263.4	19. SIGNATURE OF INSPECTOR: KEETON + BELVILLE

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	~~% CORE RECOVERY~~ % Moisture Content e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g	BLOWS
	0		SP - TAN, LOOSE, NONCEMENTED, FINE TO MEDIUM QUARTZ SAND, SUB ANGULAR TO ANGULAR, DRY		1	W.T. 24.5'	25
					2	Date 12 AUG. 76 Depth to water during drilling	14
	5			1.7	3		12
					4	W.T. 23.6'	15
			SM - REDDISH BROWN, SILTY SAND, FINE TO MEDIUM QUARTZ SAND SLIGHTLY MOIST		5	Water table reading 24 hrs. after hole completed.	33
				7.6	6		46
	10				7		49
					8		28
							26
				9.3	9		
	15						70
							83
							74
			FINE TO COARSE, SUB-ROUNDED TO ANGULAR				50
	20			11.7	10		53
			CL - MOTTLED WHITE, MAROON, PURPLE, REDDISH BROWN, SILTY CLAYSTONE, (HARD CL)	25.9	11	NOTE: BEGAN CORING AT 25.0'.	60
				22.8	12	PULL #1 25.0' TO 27.1' RUN 2.1' REC 1.5' CL 0.6'	75/0.4'
	25			71	BOX 1		
				76		PULL #2 27.1' TO 31.3' RUN 4.2' REC 3.2' CL 1.0'	
	30		CONTINUED ON SHEET #2				

App 3
16 of 23
Section F

NOTE: Soils field classified in accordance with the Unified Soil Classification System.

BLOWS PER FOOT:
Number required to drive 1⅜" ID splitspoon w/140 lb. hammer falling 30".

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE 478.1		Hole No. CS-2
PROJECT DENTAL CLINIC	INSTALLATION FT. GORDON, GA.		SHEET 2 OF 8 SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	30				BOX 1	PULL # 2 CONTINUED
				100		PULL # 3 31.3' TO 36.1' RUN 4.8' REC 4.9' CG 0.1'
	35				BOX 2	
			CL - WHITE, SILTY, MOIST MICACEOUS, VERY STIFF, KAOLIN CLAY	96		PULL #4 36.1' TO 40.9' RUN 4.8' REC 4.6' CL 0.2'
	40					
			SC - WHITE TO PINK, SILTY SAND, VERY CLAYEY WITH KAOLIN CLAY, VERY MICACEOUS, FINE TO COARSE QUARTZ SAND, IRON STAINED, VERY STIFF TO SOFT, MOIST	0	BOX 3	PULL #5 40.9' TO 45.9' RUN 5.0' REC 0.0' CL 5.0'
	45			100		PULL #6 45.9' TO 47.0' RUN 1.1' REC 2.3' CG 1.2'
				100		PULL #7 47.0' TO 51.8' RUN 1.1' REC 5.0' CG 0.2'
	50				BOX 4	
				100		PULL #8 51.8' TO 56.5' RUN 4.7' REC 4.7'
	55					
			CH - WHITE, HARD, KAOLIN CLAY	93		PULL #9 56.5' TO 60.8' RUN 4.3' REC 4.0' CL 0.3'
	60		VERY STIFF 57.5' SLICKENSIDE 30° 58.0' JOINT 65°	0	BOX 5	PULL #10 60.8' TO 65.6' RUN 4.8' REC 0.0'
	65			100		PULL #11 65.6' TO 67.0' RUN 1.4' REC 1.7' CG 0.3'
				100		PULL #12 67.0' TO 71.7' CONTINUED ON SHEET #2
	70		CONTINUED ON SHEET #2			

DRILLING LOG (Cont Sheet) ELEVATION TOP OF HOLE 478.1 **Hole No.** CS-2

PROJECT DENTAL CLINIC | INSTALLATION FT. GORDON, GA | SHEET 3 OF 8 SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	70					RUN 4.7' REC 0.5' CL 4.2'
			GRADATIONAL CONTACT			
	75		CL- MOTTLED WHITE, FE STAINED, VERY SANDY, MICACEOUS, VERY STIFF	100	BOX 6	PULL #13 71.7' TO 75.5' RUN 3.8' REC 5.4 CG 1.6'
	80		SC- CREAMY WHITE, CLAYEY, SILTY, FINE TO COARSE QUARTZ SAND, SUB ROUNDED TO ANGLUAR, MICACEOUS	36		PULL #14 75.5' TO 81.3' RUN 5.8' REC 2.1' CL 3.7'
				77	BOX 7	PULL #15 81.3' TO 82.2' RUN 0.9' REC 0.7' CL 0.2'
	85			82		PULL #16 82.2' TO 87.2' RUN 5.0' REC 4.1' CL 0.9'
	90			56	BOX 8	PULL #17 87.2' TO 92.2' RUN 5.0' REC 2.8' CL 2.2'
	95			100		PULL #18 92.2' TO 97.2' RUN 5.0' REC 5.0'
	100			100	BOX 9	PULL #19 97.2' TO 102.2' RUN 5.0' REC 6.0' CG 1.0'
	105			70		PULL #20 102.2' TO 107.2' RUN 5.0' REC 3.5' CL 1.5'
	110		CONTINUED ON SHEET #4	100	BOX 10	PULL #21 107.2' TO 112.2' RUN 5.0' REC 5.0'

DRILLING LOG (Cont Sheet) | ELEVATION TOP OF HOLE: 478.1 | **Hole No.** CS-2

PROJECT: DENTAL CLINIC | INSTALLATION: FT. GORDON, GA | SHEET 4 OF 8 SHEETS

ELEVATION (a)	DEPTH (b)	LEGEND (c)	CLASSIFICATION OF MATERIALS (Description) (d)	% CORE RECOVERY (e)	BOX OR SAMPLE NO. (f)	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) (g)
	110					PULL #21 CONTINUED
	115		114.3'-114.8' SOME KAOLIN CLAY BALLS 114.8'-117.2' WELL DEFINED BEDDING WITH THIN LENSES OF HEAVY MINERALS	94	BOX 11	PULL #22 112.2' TO 117.2' RUN 5.0' REC 4.7' CL 0.3'
	120			100		PULL #23 117.2' TO 122.2' RUN 5.0' REC 5.1' CG 0.1'
	125		124.0'-124.4' LENSE OF CL-STIFF, WHITE, KAOLIN CLAY	100	BOX 12	PULL #24 122.2' TO 127.2' RUN 5.0' REC 5.2' CG 0.2'
	130		129.5'-130.2' ORANGE STREAKS COARSE SAND UP TO 3/4" DIAMETER	98		PULL #25 127.2' TO 132.2' RUN 5.0' REC 4.9' CL 0.1'
	135		CL-LIGHT GRAY W/ORANGE MOTTLING, SANDY STIFF CLAY SC-CREAMY WHITE, CLAYEY SILTY, FINE TO COARSE QUARTZ SAND, SUB ROUNDED TO ANGULAR, MICACEOUS SAND	88	BOX 13	PULL #26 132.2' TO 137.2' RUN 5.0' REC 4.4' CL 0.6'
	140			100		PULL #27 137.2' TO 142.2' RUN 5.0' REC 5.0'
	145			62	BOX 14	PULL #28 142.2' TO 147.2' RUN 5.0' REC 3.1' CL 1.9'
	150		149.3'-149.9' CL-YELLOW, GRAY, STIFF, KAOLIN CLAY CONTINUED ON SHEET #5	88		PULL #29 147.2' TO 152.2' CONTINUED ON SHEET #5

DRILLING LOG (Cont Sheet) | ELEVATION TOP OF HOLE: 478.1 | **Hole No.** CS-2

PROJECT: DENTAL CLINIC | INSTALLATION: FT. GORDON, GA | SHEET 5 OF 8 SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	150					PULL #29 CONTINUED RUN 5.0' REC 4.4' GL 0.6'
			152.0'- 154.0' THIN HEAVY MINERAL LENSES			
	155		CL- LIGHT GRAY, STIFF TO HARD, SANDY, KAOLIN CLAY	100	BOX 15	PULL #30 152.2' TO 157.2' RUN 5.0' REC 5.2' CG 0.2'
	160		SM- LIGHT GRAY, FINE TO COARSE, SILTY, CLAYEY, MICACEOUS, QUARTZ SAND, SUB ROUNDED TO ANGULAR	100	BOX 16	PULL #31 157.2' TO 162.2' RUN 5.0' REC 5.0'
	165			100		PULL #32 162.2' TO 167.2' RUN 5.0' REC 5.1' CG 0.1'
	170		169.0'- 171.0' HEAVY MINERAL GRAINS + SMOKY QUARTZ GRAVELS 3/4" DIAMETER SUB ROUNDED	96	BOX 17	PULL #33 167.2' TO 172.2' RUN 5.0' REC 4.8' CL 0.2'
			171.0'-172.2' YELLOW STRINGERS			
	175		172.2'-172.5' CL PURPLE + ORANGE STIFF KAOLIN CLAY STRINGER 172.5'-174.3' QUARTZ GRAVELS 174.3'-175.3' CL, LIGHT GRAY, STIFF	20		PULL #34 172.2' TO 177.2' RUN 5.0' REC 1.0' CL 4.0'
			CL- DARK ORANGE, YELLOW, LIGHT GRAY, PURPLE, STIFF TO HARD, KAOLIN CLAY, SANDY, MICACEOUS	100	BOX 18	PULL #35 - CG 2.9' 177.2' TO 179.6' RUN 2.4' REC 5.3'
	180			90		PULL #36 179.6' TO 185.5' RUN 5.9' REC 5.3' CL 0.6'
	185			100	BOX 19	PULL #37 185.5' TO 190.1' RUN 4.6' REC 4.6'
	190		CONTINUED ON SHEET #6			

DRILLING LOG (Cont Sheet) | ELEVATION TOP OF HOLE: 478.1 | **Hole No.** CS-2

PROJECT: DENTAL CLINIC | INSTALLATION: | SHEET 6 OF 8 SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	190		LIGHT GRAY, HARD	98	BOX 20	PULL #38 190.1' TO 195.0' RUN 4.9' REC 4.8 CL 0.1'
	195		SC- PURPLE TO GRAY, FINE TO COARSE, SILTY, CLAYEY SAND, WITH SOME LIGHT GRAY CLAY LENSES	92		PULL #39 195.0' TO 200.1' RUN 5.1' REC 4.7' CL 0.4'
	200		SOME GRAVELS	94	BOX 21	PULL #40 200.1' TO 205.2' RUN 5.1' REC 4.8' CL 0.3'
	205			13		PULL #41 205.2' TO 209.0' RUN 3.8' REC 0.5' CL 3.3'
	210			90	BOX 22	PULL #42 209.0' TO 214.2' RUN 5.2' REC 4.7' CL 0.5'
	215		214.2'-214.8' IRON STAINED ORANGE LENSE 215.0'-219.2' POOR RECOVERY GRAVEL WASHOUT IN DRILLING MUD	30		PULL #43 214.2' TO 219.2' RUN 5.0' REC 1.5' CL 3.5'
	220		CL-MOTTLED ORANGE, PURPLE, GRAY, SANDY MICACEOUS, KAOLIN CLAY SC-LIGHT GRAY, FINE TO COARSE, SILTY, CLAYEY MICACEOUS SAND	100		PULL #44 219.2' TO 224.4' RUN 5.2' REC 5.6' CG 0.4'
	225		CL-SM-INTERBEDDED, CL-HARD, RED, PURPLE, GRAY SM-LIGHT GRAY, MICACEOUS, FINE SC-LIGHT GRAY, FINE TO COARSE, SILTY, CLAYEY, QUARTZ SAND, WITH SUB ROUNDED	50	BOX 23	PULL #45 224.4' TO 230.0' RUN 5.6' REC 2.8' CL 2.8'
	230		CONTINUED ON SHEET #7			

DRILLING LOG (Cont Sheet) ELEVATION TOP OF HOLE 478.1 **Hole No.** CS-2

PROJECT DENTAL CLINIC INSTALLATION FT. GORDON, GA SHEET 7 OF 8 SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	230		TO ANGULAR SMOKEY QUARTZ GRAVELS, HEMATITE (ORANGE) STAINS IN SAND, MICACEOUS	100	BOX 24	PULL #46 230.0' TO 235.0' RUN 5.0' REC 5.0'
	235		231.7'-232.7' CL, LIGHT GRAY, SANDY, MICACEOUS, SOFT TO FIRM, STRINGER HEMATITE (ORANGE) STAINS IN SAND, PARALLEL	90		PULL #47 235.0' TO 240.0' RUN 5.0' REC 4.5' CL 0.5'
	240		233.0' AT 20° 235.8' AT 20° 238.0' AT 20°	48		PULL #48 240.0' TO 242.9' RUN 2.9' REC 1.4' CL 1.5'
			238.5' AT 30° 238.9' AT 30°		BOX 25	
	245		242.6'-249.2' ORANGE TO YELLOW SC SANDS	69		PULL #49 242.9' TO 247.2' RUN 4.3' REC 3.0' CL 1.3'
			TOP OF ROCK 249.2'	100		PULL #50 247.2' TO 251.2' RUN 5.0' REC 5.0'
	250		GNEISS - MOTTLED, CREAMY WHITE, FE STAINED, BADLY WEATHERED, ALTERED, VERY SOFT, FOLIATED, MICACEOUS, VERY THIN, CONTINUOUS GNEISSIC BANDING			PULL #51 251.2' TO 256.2' RUN 5.0' REC 3.8' CL 1.2'
	252		250.3' AT 60° JOINT THIN QUARTZ LENSES 250.0', 251.0', 252.0'	76	BOX 26	NOTE: SCALE CHANGE AT 250.0'
	254		251.2'-253.0' ORANGE 253.0'-256.7' MOTTLED WHITE + DARK RED BROWN			
	256		MOTTLED ORANGE, BLUE-GRAY, RED	31		PULL #52 256.2' TO 260.9' RUN 4.7' REC 1.5' CL 3.2'
	258		CONTINUED ON SHEET #8			

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Section F

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE 478.1			Hole No. CS-2	
PROJECT DENTAL CLINIC		INSTALLATION FT. GORDON, GA			SHEET 8 OF 8 SHEETS

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
	258		GNEISS - MOTTLED ORANGE, BLUE-GRAY, RED			PULL # 52 CONTINUED
	260					
	262			100	BOX 27	PULL # 53 260.9' TO 263.4' RUN 2.5' REC 4.0' CG 1.5'
			SLICKENSIDES AT 263.2' 45°			
	263.4		BOTTOM OF HOLE 263.4'			

App 3
23 of 23
Section F

SECTION G

Elbert and Hart Counties, Georgia, and the Projection of the Towaliga Fault.

EVALUATION OF MAGNETIC DATA IN HEADRMONT QUADRANGLE, GEORGIA

consultant report to the
CORPS OF ENGINEERS, U.S. ARMY, SAVANNAH, GA.

20 October, 1976

by

Leland Timothy Long

Prepared at the request of Mr. William Hancock and Mr. Earl Titcomb

SUMMARY

Magnetic data taken in lines across the hypothesized fault of Roger Austin (1968) do not show evidence of faulting. However, significant anomalies were detected. If these anomalies are related to layering in the metadacite and volcanic sequences above, then a detailed magnetic survey could delineate the structures. Such a survey would require significant off-the-raod traverses.

INTRODUCTION

At the request of Mr. William Hancock and Mr. Earl Titcomb, a magnetic survey was initiated to evaluate the potential of magnetic measurements in order to evaluate the possible existence of faults proposed by Roger S. Austin in a 1968 report on the Geology of the Trotter Shoals dam site. Consequently, three magnetic lines were executed along the only three roads found to cross the possible faults.

LOCATION OF LINES

Line one is approximately 1.5km. long and extends east-west at latitude 34°02'N from 82°38.5 to 39.5'W. The end points are indicated on the portion of the Heardmont Quadrangle shown in Figure 1. The line consisted of 163 total field values at an average separation of 9 meters. Line two is 0.8km north of line one. It consists of 40 total field values but was found to be useless because of the trash along side the road. Line three crosses the southern portion of the hypothesized fault at 34°00.2'N and 82°38.5'W (see Figure 1).

INTERPRETATION OF MAGNETIC ANOMALIES

Line one (see Figure 2) shows four asymetric anomalies with the fourth from the east subdued in amplitude. The widths of the anomalies are approximately 80 meters. Unfortunately, the strike of the structure is unknown so that the width or depth of the structures can not be determined from this data alone. The asymetry indicated is one of a gradual increase in the anomaly from the west to its maximum value and a rapid decrease on the western edge. This could indicate dip to the east or northeast striking structures or both. A fifth positive anomaly is also present but its character is less certain because of interference from a steel pipe. The positive anomalies are most likely related to mafic units or dikes which approach within 50 ft. of the surface. The position of the proposed fault is also shown in Figure 2. There exists no

evidence in the magnetic data for a fault. However, the possible existence of a fault is not entirely excluded by the data.

Line two (see Figure 3) was contaminated by surface trash and could not be interpreted.

Line three (see Figure 4) shows one positve anomaly similar to the anomalies observed along line one. No evidence of a fault was observed in the magnetic data along line three. However, additional minimal data near line three could probably establish the strike of the structure causing the positive anomaly.

RECCOMMENDATIONS FOR FURTHER MAGNETIC SURVEYS

The first task of a magnetic survey would be to determine the strike of the anomalies and their cause. The Geology presented by Roger S. Austin (1968) does not appear to correlate with the anomalies along line one. If the anomalies are due to North trending Triasic diabase dikes, then the magnetics may not yield significant results concerning the older structure. If the anomalies are due to layering in the metadacite and the volcanic sequences above it in the same manner as near Lincolnton, Georgia, then a magnetic survey could effectively delineate the structures. The size of the observed anomalies would require a spacing of readings of at most 15 meters. The line spacing should be less than 0.5km. In the area of the hypothesized fault this would require off-the-road travel almost completely. The minimum area of investigation would be about 2x3km and require about 20km of traverses. Any larger area would best be surveyed with an airborne magnetometer.


Line 1.0
Line 2.0
Line 3.0
Creek
L. Clark Hill Reservoir
1 500 000 FEET (S.C.)
82°37'30"
34°00'
BEULAH 3 MI.

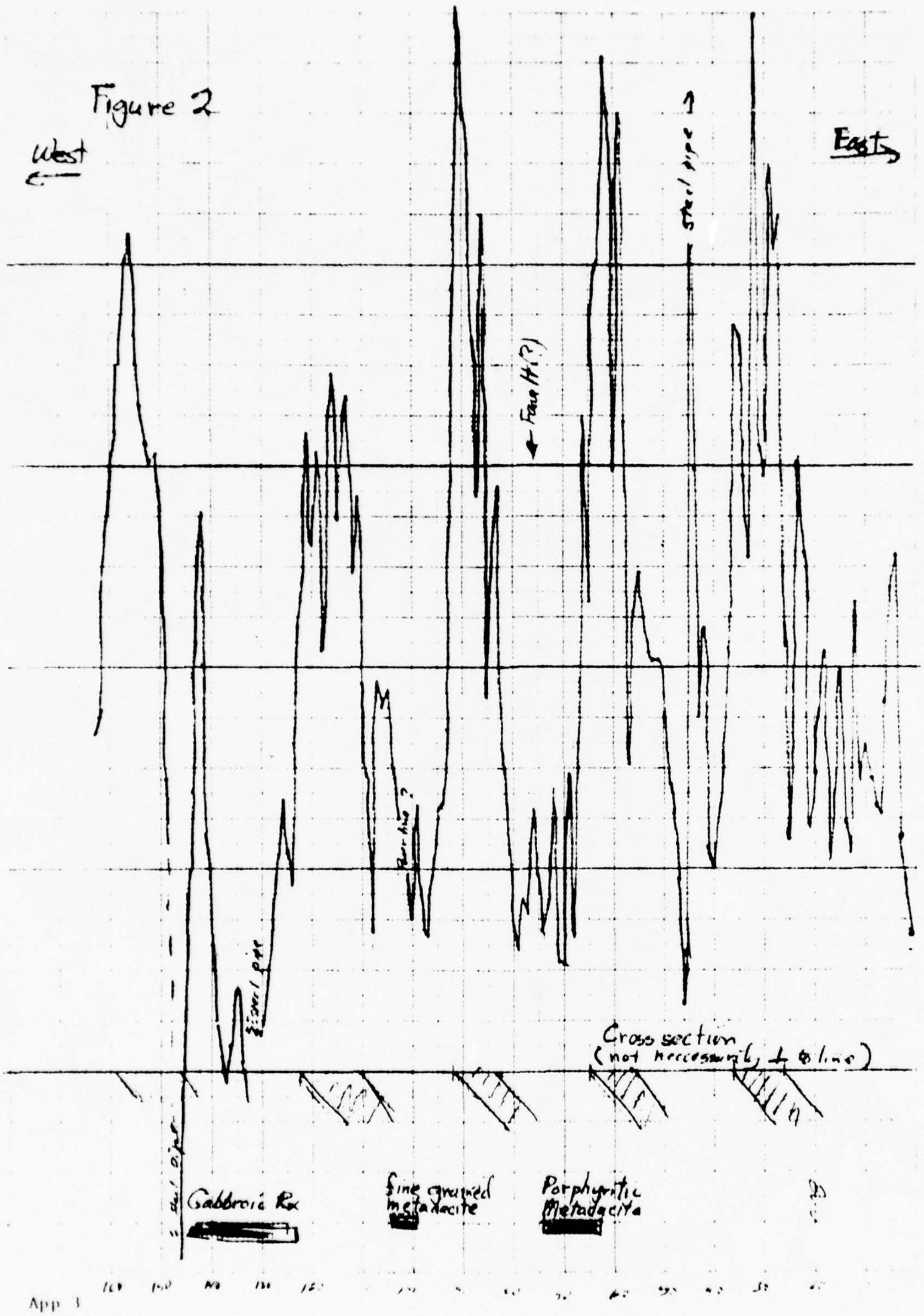
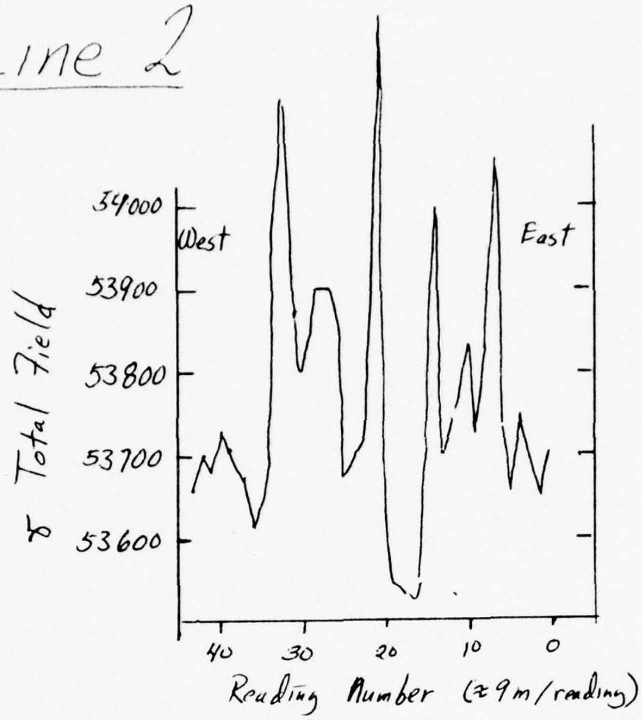


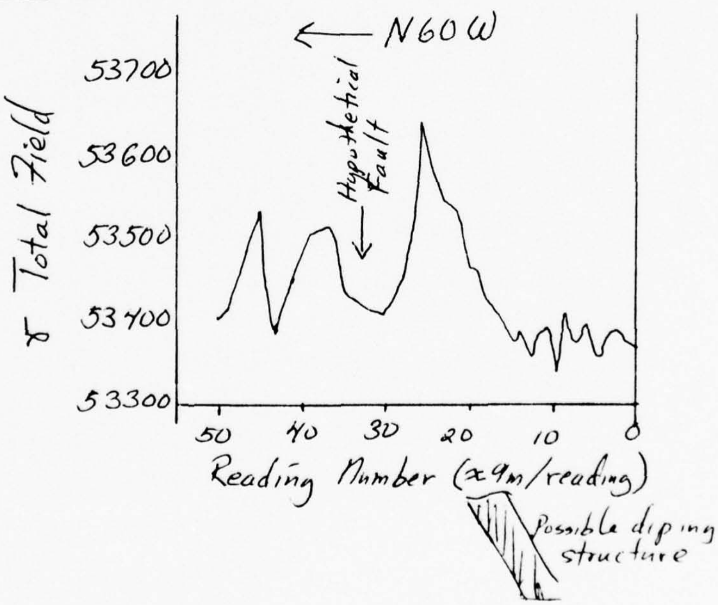
Figure 2
West
East
Steel pipe
Fault(?)
Steel pipe
Cross section
(not necessarily ⊥ to line)
Gabbroic Rx
Fine grained metadacite
Porphyritic Metadacite

Line 2



54000
53900
53800
53700
53600
West
East
γ Total Field
40
30
20
10
0
Reading Number (≈9m/reading)

Line 3



N60W
53700
53600
53500
53400
53300
Hypothetical Fault
γ Total Field
50
40
30
20
10
0
Reading Number (≈9m/reading)
Possible diping structure

GLOSSARY

A GLOSSARY OF STANDARD NOMENCLATURE, TERMINOLOGY AND DEFINITIONS

Introduction. This glossary has been prepared to define the usage of terms which appear frequently either in the text or in reference literature.

Absorption. A process whereby the energy of a seismic wave is converted into heating of the medium through which the wave passes.

Accelerogram. The record from an accelerometer showing acceleration as a function of time. See Strong Motion.

Aftershocks. Minor seismic tremors that may follow an underground nuclear detonation or the secondary tremors following the main shock of an earthquake.

Alluvium. A general term for compacted particles of rock, sand, clay, etc., deposited in relatively recent geologic times.

Amplification. Frequency dependent modification of the input bedrock ground motion characteristics by the local soil column. Amplification causes the amplitude of the surface ground motion to be increased in some range of frequencies and decreased in others. Amplification is a function of the shear modulus and damping of the soil, its thickness, and its geometry.

Amplitude. Maximum deviation from mean or center line of wave.

Anisotropic Mass. A material having different properties in different directions at any given point.

Anisotropy. Variation of a physical property depending on the orientation along which it is measured.

Annual Risk. The annual risk associated with a given intensity is defined as the probability that, in any given year, that intensity will be equaled or exceeded. The annual risk is also the reciprocal of the mean annual return period. This technical definition of the word risk, as a probability, has been questioned. It is not consistent with another technical definition used in statistical decision theory which associates the word risk with an expected loss (a probability of loss time values of the loss), but the definition here is totally consistent with both popular and dictionary definitions of the word, i.e., the chance of something undesirable. Therefore, unless and until an equally connotative and convenient alternative is coined, the writers suggest that this use of the word risk is quite appropriate.

Anomaly. A deviation from uniformity or normality.

Attenuation.

1. A decrease of signal magnitude during transmission.

2. A reduction in amplitude or energy without change of waveform.

3. The decrease in seismic signal strength with distance which does not depend on geometrical spreading but may be related to physical characteristics of the transmitting media causing absorption and scattering.

Bar. = one atmosphere: A unit of pressure, approximately 14.5 psi.

Basement. The igneous, metamorphic or highly folded rock underlying sedimentary units below which there is no current economic interest.

Bedrock. Any solid rock exposed at the surface or underlying soil; has shear wave velocity 6,000 ft/s (1,828 m/s). See Firm soil and Soft soil.

Body Wave Magnitude. See Magnitude.

Body Waves. Waves propagated in the interior of a body, i.e., compression and shear waves, the P and S waves of seismology.

Capable Fault. A capable fault is one that can be shown to exhibit one or more of the following characteristics:

1. Movement at or near the ground surface at least once within the past 35,000 years.

2. Macro-seismicity ($\geq 3.5M$) instrumentally determined with records of sufficient precision to demonstrate a direct relationship with the fault.

3. A structural relationship to a capable fault according to characteristics 1 and 2 above, such that movement on one could be reasonably expected to be accompanied by movement on the other.

Critical Damping. The minimum viscous damping that will allow a displaced system to return to its initial position without oscillation.

Crust. The outermost shell of the earth; the portion above the Mohorovicic discontinuity.

Damping. Resistance which slows down or opposes oscillations. Critical damping, μ_c, is the minimum damping which will prevent oscillation from taking place. See Response Spectrum.

Design Earthquakes. Design earthquakes define the ground motion at the site of the structure and form the bases for dynamic response analyses. Generally, several design earthquakes for both the maximum earthquake and the operating basis earthquake, as applicable, are investigated.

Dip-Slip Fault. A fault whose principal displacement is parallel to the dip of the fault.

Displacement.

1. The distance a particle is removed from its equilibriam position, as in the ground motion associated with a seismic wave.

2. The integral of the velocity of ground particles as recorded by a seismograph.

3. The relative movement of the two sides of a fault.

Dynamic Soil Properties. Those soil properties which affect the response of soils subjected to cyclic loading conditions.

Earthquake Waves. Groups of elastic waves propagating in the earth, set up by a transient disturbance of the elastic equilibrium of a portion of the earth.

Elastic Constants. See Modulus.

Elastic Waves. = seismic waves, earthquake waves: P, S, Love, Rayleigh.

Epicenter. In an earthquake, the point on the earth's surface vertically above the hypocenter, the location in space where first motion occurs.

Failure. A condition in which movement caused by shearing stresses in a structure or soil mass is of sufficient magnitude to destroy or seriously damage it.

Fault. A fracture or fracture zone along which there has been displacement of the two sides relative to one another parallel to the fracture. See Normal, Dip-slip, Thrust and Strike-slip faults.

Firm Soil. A general term for soil characterized by a shear wave velocity $\geq$ 2,000 ft/s (609 m/s). See Soft Soil, Bedrock.

Focal Depth. The vertical distance between the hypocenter and the earth's surface (epicenter) in an earthquake (or aftershock).

Focus. The point within the earth which marks the origin of the elastic waves of an earthquake.

Frequency. Number of cycles occurring in unit time.

Geophysics. The study of the physical characteristics and properties of the earth.

Ground Response, Motion, or Seismic Response. A general term, includes all aspects of motion, viz., particle acceleration, velocity, or displacement; stress and strain, usually resulting from a nuclear blast or an earthquake.

Hertz. = hz = cycles per second = cps: A unit of frequency.

Hydrostatic Pressure. The pressure in a liquid under static conditions; the product of the unit weight of the liquid (water = 62.4 pcf) and the difference in elevation between the given point and the ground water elevation.

Hypocenter. The location in space where the slip responsible for an earthquake occurs; the focus of an earthquake or aftershock.

In Situ Strength. The in-place field strength of a soil or rock deposit.

Intensity. A numerical index describing the effects of an earthquake on man, on structures built by him and on the earth's surface. The number is rated on the basis of an "earthquake intensity scale," the scale in common use in the U.S. today is the Modified Mercalli Scale of 1931 with grades indicated by Roman numerals from I to XII.

Internal Friction. The resisting shear strength considered to be due to the interlocking of the soil grains and the resistance to sliding between the grains.

Isotropic. Having the same physical properties regardless of the direction in which they are measured. Strictly applies only to an arbitrarily small neighborhood surrounding a point and to single properties.

Least Squares Fits. An analytic function which approximates a set of data such that the sum of the squares of the distances from the observed points to the curve is a minimum.

Linears. As intended in this study, linears are straight features of topography extending usually for a few miles. Lineaments are long linears or combinations of linears. See also discussion of Linear in text.

Lithology. The description of rock composition and texture.

Loading. The force on an object or structure or element of a structure.

Longitudinal Wave. = compression wave = p wave.

Love Wave. A seismic surface wave which propagates in a surface layer. The vibration is transverse to the direction of propagation with no vertical motion.

Magnitude. A quantity characteristic of the total energy released by an earthquake, as contrasted to "intensity," which describes its effects at a particular place. Professor C. F. Richter devised the logarithmic magnitude scale in current use, which is in terms of the motion which would be measured by a standard type of seismograph located 100 kilometers from the epicenter of an earthquake. Several magnitude scales are in use, e.g.; body wave magnitude, surface wave magnitude which utilize body waves and surface waves, respectively. The scale is open ended, but the largest known earthquake magnitudes are near 8.9.

Major Principal Stress (see Principal Stress) - The largest (with regard to sign) principal stress.

Maximum Earthquake. The maximum earthquake is defined as the severest earthquake that is believed to be possible at the site on the basis of geological and seismological evidence. It is determined by regional and local studies which include a complete review of all historic earthquake data of events sufficiently nearby to influence the project, all faults in the area, and attenuations from causative faults to the site.

Mantle. The part of the earth's interior between the core and the crust. The upper surface of the mantle is the Mohorovicic discontinuity.

Meizoseismal Zone. Zone of intense shaking in the near field of an earthquake. The radial width of this zone increases with magnitude.

Microtremor. A feeble earth tremor resulting from natural or man-made forces, i.e., micro-earthquake, micro-seismic.

Minor Principal Stress (see Principal Stress) - The smallest (with regard to sign) principal stress.

Model. A concept from which one can deduce effects that can then be compared to observation which assists in developing an understanding of the significance of the observations. The model may be conceptual, physical, or mathematical.

Mohorovicic (M) Discontinuity. Seismic discontinuity which separates the earth's crust and mantle.

Normal Stress. That stress component normal to a given plane.

Normal Fault. Vertical movement along a sloping fault surface in which the blockabove the fault has moved downward relative to the block below.

Operating Basis Earthquake. The "operational" earthquake is generally more moderate than the maximum earthquake and is selected on a probabilistic basis from regional and local geology and seismology studies as being likely to occur during the life of the project. It is generally as large as earthquakes that have occurred in the seismo-tectonic province in which the site is located.

Overburden. The generic term applied to uppermost layers of the geologic structure, usually soil layers of low seismic velocity, overlaying rock or other high seismic velocity strata.

P Wave (see also Compression or Body Wave) - Body wave in which the direction of the particle movement is the same as the direction of wave propagation. Wave velocity is commonly measured in geophysical refraction surveys to define the contact between the dynamic properties of competent rock layers (high velocity materials) and softer or less competent soil layers (low velocity materials).

Particle Acceleration. The time rate of change of particle velocity.

Particle Displacement. The difference between the initial position of a soil particle and any later position.

Particle Velocity. The time rate of change of particle displacement.

Period. Time interval occupied by one cycle.

Permeability. A measure of the ease with which a fluid can pass through the pore spaces of a formation.

Phase. The angle of lag or lead (or the displacement) of a sine wave with respect to a reference; the stage in the period in which rotation, oscillation, or variation has advanced, considered in relation to a reference or assumed instant of starting.

Poisson's Ratio. The ratio of the transverse contraction to the longitudinal extension when a rod is stretched. The ratio of the velocities of P waves, V_P and V_S , can be expressed in terms of Poisson's ratio, σ:

$$\frac{V_P}{V_S} = \frac{2(1-\sigma)}{(1-2\sigma)}$$

Pore Water Pressure. Pressure or stress transmitted through the pore water (water filling the voids of the soil or rock).

Principal Stress. Stresses acting normal to three mutually perpendicular planes intersecting at a point in a body, on each of which the shearing stresses are zero.

Pulse. A waveform whose duration is short compared to the time scale of interest and whose initial and final values are the same (usually zero).

Rayleigh Wave. = R wave: A type of seismic surface wave which propagates along the surface. Particle motion is eliptical and retrograde in the vertical plane containing the direction of propagation and its amplitude decreases exporentially with depth.

Response. The motion in a system resulting from an excitation under specified conditions.

Response Spectrum. The response of a series (or spectrum) of simple oscillators, with a postulated damping ratio, subjected mathematically to a particular ground motion. The response spectrum may be plotted as a curve on tripartite logarithmic graph paper showing the variations of the peak spectral acceleration, displacement and velocity of the oscillator with its vibration period. See Damping.

Rock. See Bedrock.

S Wave (Shear Wave). Body wave in which the particle motion is at right angles to the direction of wave propagation. SH and SV denotes planes of polarization of wave. Wave velocity may be measured by in-hole geophysical procedures to determine the dynamic shear moduli of the materials through which the wave passes.

Seismic Wave. An elastic wave generated by an earthquake or explosion which causes only a temporary displacement of the rock medium, the recovery of which is accompanied by ground vibrations.

Seismogram. A record of ground motion or of the vibrations of a structure caused by a disturbance, such as an underground detonation or an earthquake.

Seismograph. A system for amplifying and recording the signals from seismometers.

Seismometer. The instrument used to transform seismic energy into an electrical voltage. Most seismometers are velocity detectors, their outputs being proportional to the velocity of the inertial mass with respect to the seismometers case (which is proportional to the velocity of the earth motion). But below the natural frequency, the response of most geophones decreases linearly with frequency so that they operate as accelerometers.

Shear Wave. - S wave - transverse wave: A body wave in which the particle motion is perpendicular to the direction of propagation.

Standard Deviation. The standard deviation, σ , of n measurements of a quantity X , with respect to the mean, $\bar{X}$, is:

$$\sigma = \left(\frac{1}{N-1} \sum_{i=1}^{N} (X_i - \bar{X})^2\right)^{1/2}$$

Strain. The change in length per unit of length in a given direction which a body subjected to deformation undergoes.

Stratigraphy. The order of succession of the different sedimentary rock formations in a region.

Strength of Earthquake. Generally expressed in terms of the peak ground acceleration recorded or predicted for a particular earthquake, expressed usually in g units, where lg is an acceleration equal to that of gravity, or 980 cm/sec^2 .

Strike-Slip Fault. A fault in which movement is principally horizontal.

Strong Motion. Ground motion of sufficient amplitude to be of engineering interest in the evaluation of damage due to earthquakes or explosions.

Structural Features. Features such as faults and folds which are produced in the rock by movements after deposition, and commonly after consolidation, of the sediment.

Surface Waves. Seismic energy which travels along or near the surface. Includes Rayleigh and Love waves.

Surface Wave Magnitude. See Magnitude.

Tectonic Province. As defined by the AEC, it is a region of the North American continent characterized by the uniformity of the geologic structures contained therein.

Thrust Fault. An inclined fracture along which the rocks above the fracture have apparently moved up with respect to those beneath.

Transverse Wave. See Shear Wave.

Tuff. Various types of consolidated particulate material of volcanic origin.

Vibration. An oscillation wherein the quantity is a parameter that defines the motion of a mechanical system.

Viscosity. The cohesive force existing between particles of a fluid which cause the fluid to offer resistance to a relative sliding motion between particles; internal fluid friction.

Wave Length. Normal distance between two wave fronts with periodic characteristics in which amplitudes have a phase difference of one complete cycle.

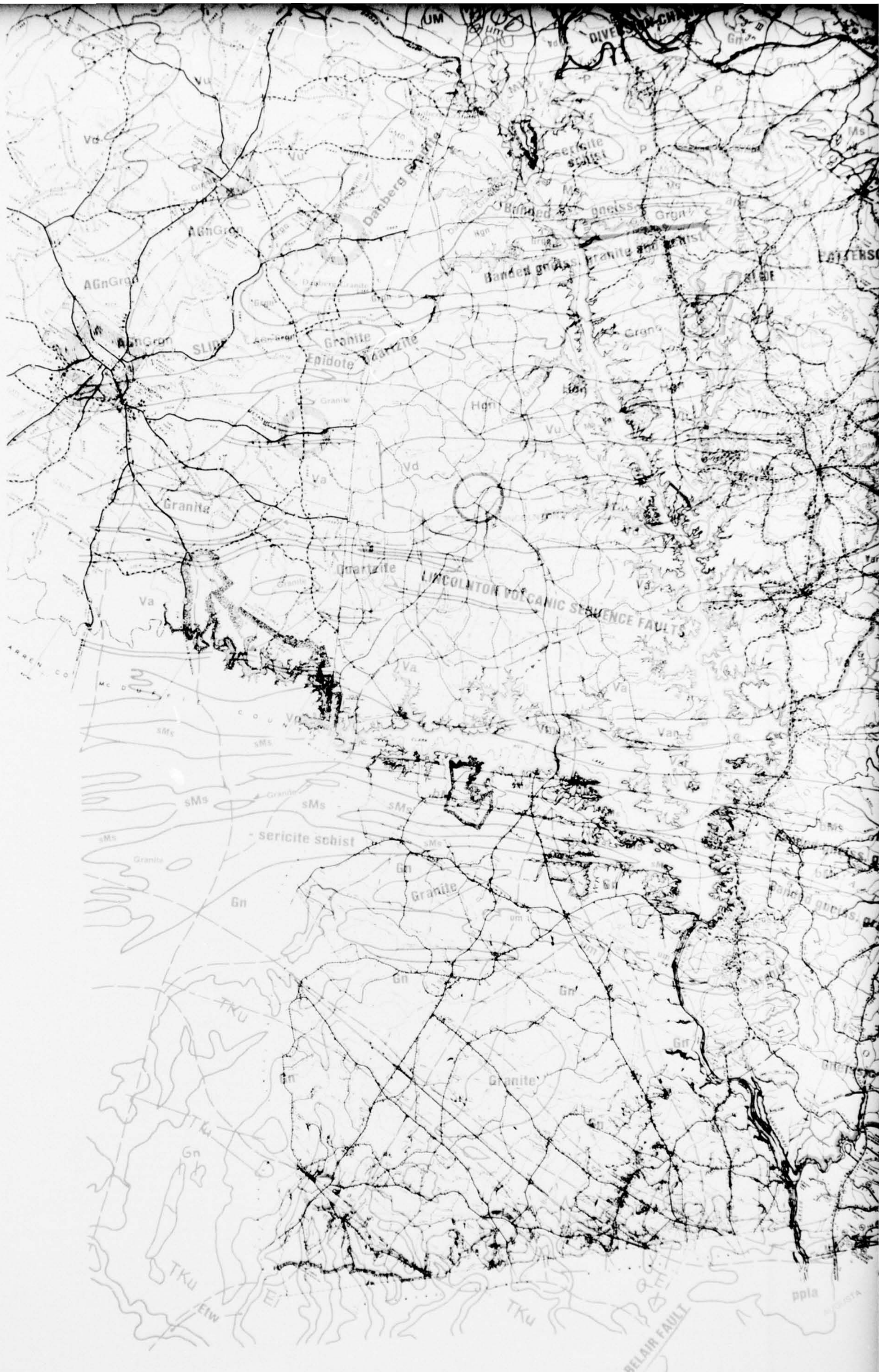

bGn
AGn
bGn
bGn
Bowman
bGnms
SS
SS
SLIDE
AGn
Elberton Granite
Elberton Granite
Elberton
MaAGnms
Gn
Ma AGnms
UM
Danberg Granite
AGnGrgn

6

2


PICKENS COUNTY
LAURENS COUNTY
KINGS MOUNTAIN ZONE
BRANCH FAULT
bgms
Gneiss

3



Danberg Granite
sericite schist
Banded gneiss
Grgn
Banded gneiss, granite and schist
AGnGrgn
SLIDE
Granite
Epidote
Quartzite
Vu
Vd
Va
Hgn
LINCOLNTON VOLCANIC SEQUENCE FAULTS
sMs
sericite schist
Gn
Granite
um
TKu
Ei
Etw
BELAIR FAULT
ppla


PATTERSON BRANCH FAULT
1974
GREENWOOD COUNTY
GOAT ROCK ZONE
BELAIR FAULT
ppla

4

GEOLOGIC LEGEND

INNER PIEDMONT CORE

bGn	Biotite gneiss
AGn	Feldspathic amphibolite gneiss and biotite-plagioclase gneiss, with migmatite.
BGGn	Biotite granodiorite gneiss, biotite-feldspar-gneiss and augen gneiss.
SS	Interlayered biotite-plagioclase gneiss, amphibolite, quartzite and mica schist. Strata dominated by sillimanite-mica schist with abundant porphyroblastic muscovite.
SgSch	Sillimantie-graphitic schist.
pss	Porphyroblastic sillimanite in sillimanite-mica schist.
Stms	Staurolite-mica schist.
bGnms	Composit-layered gneiss and mica schist.
MGr	Muscovite granodiorite including pegmatitic and porphyritic types.
bgms	Migmatic assemblages of biotite gneiss, mica-schist and sillimanite as accessory mineral.
Ma	Metagabro associated with amphibolite and amphibolite gneiss.
GrGn	Feldspar-granitic gneiss.
Ms	Mica schist, biotite-muscovite-sericite mica schist, may be garnetiferous.
Grms	Quartzofeldspathic gneiss and mica schist.

INNER PIEDMOND FLANK

GrbGn	Granitoid rocks, biotite gneiss, quartzofelds-pathic gneiss and quartzite.
MaAGn	Amphibolite, amphibolite gneiss, hornblende, andesine, pyroxene injection gneiss and schlieren.

LOWNDESVILLE BELT

MaAGn	Amphibolite and qugen gneiss.
MS	Mica schist, biotite schist and sericite-muscovite schist.
GrbGn	Granitoid rocks, biotite gneiss and quartzofelds-pathic gneiss.
bgms	Biotite gneiss and mica schist.

CHARLOTTE BELT

MaAGnms	Amphibolite, amphibolite gneiss, hornbl acid feldspar, pyroxene injection gneis schlieren interlayered with mica schist
AGnms	Amphibolite gneiss and biotite-mica sch
P	Quartz-muscovite schist and quartzose
bgms	Biotite gneiss and mica schist.
UM	Ultramafic and Gabbroid complexes.
a	hornfels-amphibolite aureole.
Grgn	Granitoid gneiss and quartzofeldspathic Adamellite composition in the core.
Hgn	Hornblende gneiss.
AGnGrgn	Amphibolite gneiss and granitic gneiss entiated.
Epidote Quartzite sericite Schist	as stated.

CAROLINA SLATE BELT OF SOUTH CAROLINA AND LITTLE RIVER SERIES OF GEORGIA

VOLCANICS

V 1	Metasediments and conglomerates.
V	Hornblende ribbon gneiss.
V 2	Epidote-hornblende gneiss and meta-basal
V 3	Biotite-quartz-mica-feldspar gneiss, po
V 4	Quartz sericite schist and felsic volca
V 5	Metadacite, non-porphyritic, and tuffs.
Vd	Lincolnton type-metadacite, quartz phop
Vu	Volcanics undifferentiated.
Ma Vm	Mafic to intermediate metavolcanics.

Stratigraphy:

A schematic se
Richard B. Russell
indicated by Secti
Figure 3.)
The knowledge
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thick vegetative c
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opposed to formati
information.
Map 1 illustr
sists of approxima
volcanic rocks int
sessing highly mob
canic rocks intru
immediate vicinity
to Permian.
The age relat
shown in Figure 6.
tary and volcanic
Mountain-Loundesvi
stratigraphic sequ
each contain grayw
tuff and lava. Sp
bedded with the ma

absent. Each sequ
parts of successiv
tend from the Bre
street (1970) inf
an immense volu
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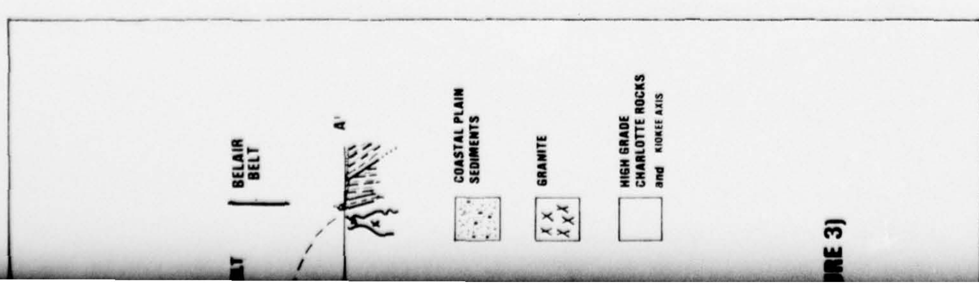

6

OLOGIC LEGEND

BELT

Amphibolite, amphibolite gneiss, hornblende-acid feldspar, pyroxene injection gneiss and schlieren interlayered with mica schists.

Amphibolite gneiss and biotite-mica schist.

Quartz-muscovite schist and quartzose phyllite.

Biotite gneiss and mica schist.

Ultramafic and Gabbroid complexes.

hornfels-amphibolite aureole.

Granitoid gneiss and quartzofeldspathic gneiss, Adamellite composition in the core.

Hornblende gneiss.

Amphibolite gneiss and granitic gneiss undifferentiated.

rtzite
ist

as stated.

LATE BELT OF SOUTH CAROLINA RIVER SERIES OF GEORGIA

Metasediments and conglomerates.

Hornblende ribbon gneiss.

Epidote-hornblende gneiss and meta-basalt.

Biotite-quartz-mica-feldspar gneiss, porphyritic.

Quartz sericite schist and felsic volcanics.

Metadacite, non-porphyritic, and tuffs.

Lincolnton type-metadacite, quartz phophory.

Volcanics undifferentiated.

Mafic to intermediate metavolcanics.

CAROLINA SLATE BELT OF SOUTH CAROLINA AND LITTLE RIVER SERIES OF GEORGIA

Va Felsic metavolcanics.

Var Meta-argillite and metavolcanics.

Vp Metavolcanics, sericite phyllites.

P Quartzose phyllites and phyllitic schist.

Ms Mica schist.

bgms Biotite gneiss and mica schist.

Vm Basic to andesitic volcanics and meta-basalt.

MODOC - GOAT ROCK ZONE

SMs Sericite-mica schist, including granitic gneiss and felsic gneiss.

bMs Button-mica schist, fish-scale schist, including cataclastic gneiss and augen gneiss.

KIOKEE BELT

Gn Quartz-feldspar gneiss, hornblende gneiss, quartzite and sillimanite schist. Also undifferentiated within the belt is chlorite schist and amphibolite.

BELAIR BELT

ppla Meta-argillite and phyllite.

Va Felsic metavolcanisc.

COASTAL PLAIN

Ei Eocene age, Irwinton sand

Etw Twiggs Clay

Tku Tuscaloosa Formation

DATA SOURCE USED IN MAP

Area	Author
Hart County, GA..............	Grant (1958); Baker (1933); U.S. Army Corps of Engineers (1960)
Anderson County, SC & Pickens County, SC.........	Griffin (1974b, a, 1972b; 1971a, b; 1970, 1969)
Abbeville County, SC..........	Griffin (1972a)
Elbert County, GA............	Austin (1968, 1965); Chandler (1972); Penley and Sandrock (1973)
McCormick County, SC..........	Medlen (1968); Griffin (1972a); Secor (1977); Johnson (1970); Bell (1966); Overstreet & Bell (1965a)
Lincoln County, GA...........	Crawford (1968a); Crickmay (1952); Fouts (1966); Paris (1976); Peyton & Cofer (1950); Hurst, Crawford & Sandy (1966)
Wilkes County, GA............	Peyton (1950); Fouts (1966); Crawford (1968a); Cook (1966)
Columbia County, GA..........	McLemore (1965); O'Connor & Prowell (1976); Daniels (1974)
Edgefield, SC................	Johnson (1970b); Daniels (1974); Pirkle (per. com., 1976)

Stratigraphy:

A schematic section of the rock sequences for the stratigraphy of the Richard B. Russell Dam and Lake and the additional surrounding area is indicated by Section A-A in Figure 4. (See the location of Figure 4 in Figure 3.)

The knowledge of stratigraphy in this area is incomplete. Metamorphism, lack of marker beds, faulting, saprolization, lateritization and thick vegetative cover have made the area difficult to interpret. The discussion of the stratigraphy is here presented in terms of lithology as opposed to formational names because of a lack of detailed stratigraphic information.

Map 1 illustrates the general geology of the area. The section consists of approximately 124 km (412,000 feet) of metamorphic sedimentary and volcanic rocks intruded by granite, gabbro, injected by serpentine and possessing highly mobilized cores of gneiss with migmatitic flanks. Metavolcanic rocks intruded by gabbro and gneiss are the predominant rocks in the immediate vicinity of the damsite. The geoligic age ranges from Precambrian to Permian.

The age relationships of the parent rocks in the various belts are shown in Figure 6. Overstreet (1970) states that the metamorphic sedimentary and volcanic rocks in the Caroline Slate belt, Charlotte belt, Kings Mountain-Loundesville belt, and Inner Piedmont belt consists of three stratigraphic sequences separated by two unconformities. These sequences each contain graywackies, shale, felsic and mafic tuffaceous sediments, tuff and lava. Sparce conglomeratic sandstone and limestone are interbedded with the main components. However, in the study area, limestone is absent. Each sequence was deposited in a subsiding basin with the western parts of successive basins superimposed on each other. The sequences extend from the Brevard Zone to as far as the continental shelf area. Over-

Lithology:

The rocks in the study area have been subjected to various degrees of metamorphism. Adjacent to the damsite, they are intermediate in metamorphic grade. Both regional and contact metamorphism have been operative in the area. The metadacites adjacent to the dam are uppergreenschist grade. A contact aurole of hornfels most probably surround the margin of the Calhoun Falls gabbro complex, but little evidence is found of contact metamorphism in the area of the damsite. Gabbroic dikes, however, are hydrothermally altered to give chlorite schists. These dikes are pervasive throughout the damsite.

Downstream of the damsite in the area of Clark Hill Lake, the Slate belt rocks are generally greenschist grade and exhibit less metamorphic alteration.

Upstream of the damsite, metamorphic grade increases, although the Loundesville belt has evidence of retrograde metamorphic features.

The fine grained rocks exhibit well developed foliation and slaty cleavage. They have been altered by metamorphic process into slates and phyllites. The coarser clastics and mafic flows occur as hard well indurated granitoid gneiss and amphibolite. The Inner Piedmont is separated by a discontinuity between quartzofeldspathic gneiss and the higher grade silliminite schists, gneiss and amphibolite. In cataclastic zones, all rocks are crenulated and broken with some evidence of retrogression.

The rocks in the study area may be categorized as follows:

Belair Belt: Siltstones and tuffs have undergone metamorphism to produce phyllites and greenstones which make up the belt.

Kiokee Belt: Sandstones, wackies, igneous complexes and ultra-basic rocks are through metamorphism gneiss, pyroxene garnet rock, chlorite schists and amphibloite. In the Kiokee belt, also present are quartz-feldspar-gneiss, hornblende gneiss, quartzite and sillimanite schist. Adamellite intrudes all of the above. Generally, the grade runs high into

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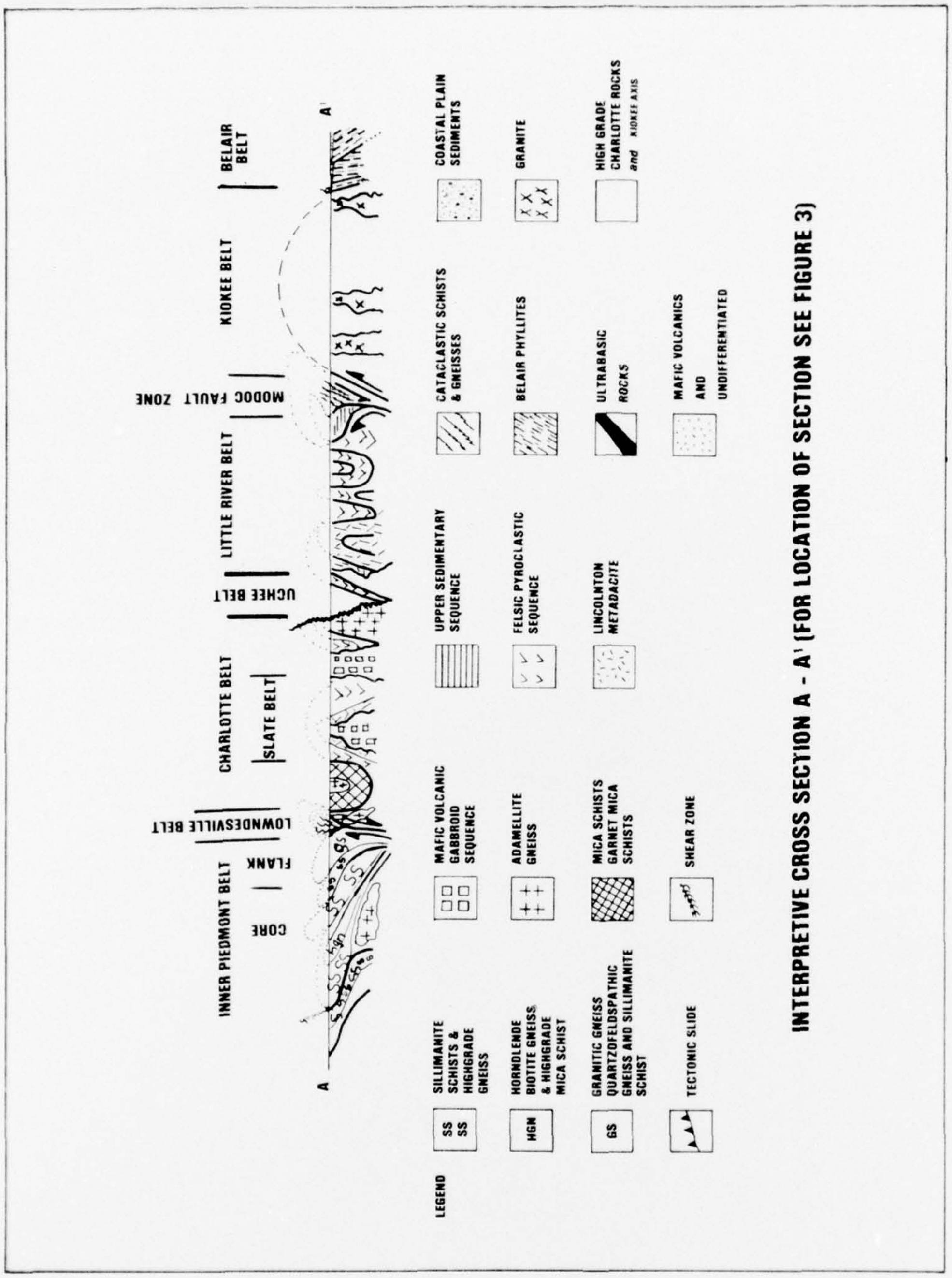

INTERPRETIVE CROSS SECTION A - A' (FOR LOCATION OF SECTION SEE FIGURE 3)
A
A'
INNER PIEDMONT BELT
CORE
FLANK
LOWNDESVILLE BELT
CHARLOTTE BELT
SLATE BELT
UCHEE BELT
LITTLE RIVER BELT
MODOC FAULT ZONE
KIOKEE BELT
BELAIR BELT
LEGEND
SS SS SS
SILLIMANITE SCHISTS & HIGHGRADE GNEISS
HGN
HORNBLENDE BIOTITE GNEISS & HIGHGRADE MICA SCHIST
GS
GRANITIC GNEISS QUARTZOFELDSPATHIC GNEISS AND SILLIMANITE SCHIST
TECTONIC SLIDE
MAFIC VOLCANIC GABBROID SEQUENCE
ADAMELLITE GNEISS
MICA SCHISTS GARNET MICA SCHISTS
SHEAR ZONE
UPPER SEDIMENTARY SEQUENCE
FELSIC PYROCLASTIC SEQUENCE
LINCOLNTON METADACITE
CATACLASTIC SCHISTS & GNEISSES
BELAIR PHYLLITES
ULTRABASIC ROCKS
MAFIC VOLCANICS AND UNDIFFERENTIATED
COASTAL PLAIN SEDIMENTS
GRANITE
HIGH GRADE CHARLOTTE ROCKS and KIOKEE AXIS

FIGURE A.

Figure 3.)

The knowledge of stratigraphy in this area is incomplete. Metamorphism, lack of marker beds, faulting, saprolization, lateritization and thick vegetative cover have made the area difficult to interpret. The discussion of the stratigraphy is here presented in terms of lithology as opposed to formational names because of a lack of detailed stratigraphic information.

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The lower sequence of Overstreet is probably Upper Precambrian or Cambrian in age. The lower sequence is the infrastructure over which the Carolina Slate belt lies (see Figure 6). Hurst has the opinion that between the Little River Series (Slate belt rocks which are traceable into Georgia) and the upper Precambrian rocks in the Blue Ridge lies a vast area of mica schist, gneiss and quartzite whose stratigraphic significant is obscured by numerous faults of unknown displacements.

*Although exact time stratigraphy in the study area is not fully under*stood, Figure 7 illustrates relationships indicated by the study of the area and those developed by others in the literature listed in Table I.

Proceeding from southeast to northwest, the first and youngest strata is the Late Cretaceous Tuscaloosa Formation. This formation marks the western edge of the Coastal Plain. This clastic formation is coarse grained, kaoline bearing, crossbedded sands and gravels. Occurring as erosional remnants below the clastic sediments of the Tuscaloosa Formation is the extremely saprolitic phyllites of the Belair belt.

Saprolite developed on the surface of the Belair belt has been preserved by post-Cretaceous burial. The Belair belt is composed of metavolcanic tuffs and argillites. The Belair belt is thought to be equivalent to the Little River Series of Crickmay (1952). The Belair belt is probably Cambrian in age. Extensive time hiatus occurred between the Permian and the Cretaceous. During this interval, extensive Belair and Little River Series thickness were stripped and section removed. In periods of quies*cence, the thick saprolite was developed on the Belair phyllites.*

The Kiokee belt is exposed west of the Fall line. This belt is the oldest rock in the study area. The exact age of the Kiokee belt is unknown, but thought to be late Precambrian or early Paleozoic. In South Carolina, the rocks of the Keokee belt are amphibolites and granitic gneiss. In Georgia, the rocks are felsic gneiss whose protoliths were igneous plutonic rocks, (quartzose sediments horndblende gneiss). Probably during Precambrian time, coarse grained gneiss were intruded into the belt, and concordant ultrabasic rocks were injected and altered to serpentine. During Ordovician time, a younger medium grained adamellite was intruded into the belt.

To the west of the Kiokee belt and overlying it are the rocks of the Carolina Slate belt. The Carolina Slate belt and its equivalent in Georgia, the Little River Series, is Paleozoic in age. The oldest sequence in the Little River Series of Georgia has been dated radiometrically to be 560-570 million years old by Carpenter (1976). This sequence is a quartz porphory *(metadacite) whose parent was a series of volcanic flows and tuffs.* Two main bodies of metadacite lie in the study area, one centered around Lincolnton, Georgia, and the second around the location of the Russell Dam.

Overlying the metadacite is an extensive series of pyroclastic debris. The most abundant lithologies are vitric and vitric crystal tuffs, lapalli tuffs, aggrolomerates, welded tuffs and mafic tuffs. Also present are some felsic and mafic flows interfingered with volcanic greywackies and argillites. Overlying the pyroclastic sequence is an upper sedimentary sequence. This consists of banded argillite and volcanics. The youngest sequence is well exposed west northwest of the modoc Fault Zone in South Carolina. Intruded into the Little River Series is the Goshen Granite which Paris (1976) thinks to be of 365 million years probable age. Rhyolite dikes present in the Little River Series yield radiometric age of 365 million years before the present (M.Y.B.P.) and are associated with oval bodies such as the Goshen Granite. Triassic diabase dikes pervasively invate the Little River Series.

The Little River Series overlie the Charlotte belt. The Charlotte belt in South Carolina consists of adamellite gneiss, quartz-epidote-hornblende gneiss, mica schist, hornblende granodiorite gneiss, granitoid gneiss and other mixed gneiss. These rocks are thought to be derived from older igneous rocks, quartzose sediments, wackies, shales, felsic and mafic tuffaceous volcanics, sediments and volcanics. In Georgia, the Charlotte belt consists of extensive areas of granitoid gneiss, high grade schists, gneiss and amphibolite. The protoliths of these rocks were intermediate to mafic metasedimentary rocks and igneous plutons. The Charlotte belt is Precambrian to Cambrian in age. The exact stratigraphic relationship between the Charlotte and Slate belt rocks in the study area is uncertain because the boundary is poorly defined. Certain relationships indicated that higher metamorphic grade is the only separating factor. When structural demonstration shows Charlotte belt rocks to be centers of anticlinora, these rocks are felt to be older than the Slate belt; however, units unrelated by simple stratigraphy exist along shear zones and faults.

Another area of stratigraphy which is not fully understood is the relationship of the Charlotte and Inner Piedmont belts to the Kings Mountain-Loundesville belt. In South Carolina, the Kings Mountain belt separates the Inner Piedmont from the Charlotte belt and is thought to show clearly younger age. Griffin (personal communication, 1976) has the opinion that the Caroline Slate belt is supracrustal; in addition, the Charlotte belt and the Inner Piedmont are infracrustal. The Loundesville-Kings Mountain belt becomes the detachment zone between adjacent older rocks. Using this scheme, the Kings Mountain belt is overlying the older Inner Piedmont and younger than the adjacent Charlotte Belt. The adjoining area in Georgia lacks the Loundesville belt. As the Loundesville belt crosses the Savannah River, foliation and bedding wrap around the nose of the syncline and the belt pinches out (Griffin, 1976, personal communication). The mica schist, gneiss quartzite and amphibolite of South Carolina do not display any clear significance in Georgia. The area may be obscure as Hurst (1970) believes by numerous faults of unknown displacement.

Gabbro, diorite, syenite, hornfels, and chloritic rocks intruded in the Slate Belt, Charlotte belt and Inner Piedmont are approximately implaced 380-386 M.Y.B.P.

the area. The metadacites adjacent to the dam are uppergreenschist grade. A contact aurole of hornfels most probably surround the margin of the Calhoun Falls gabbro complex, but little evidence is found of contact metamorphism in the area of the damsite. Gabbroic dikes, however, are hydrothermally altered to give chlorite schists. These dikes are pervasive throughout the damsite.

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Little River Series: Dacite, mafic and vitric tuff, lava, pyroclastic sequences and sediments make up the Little River Series. Mostly, those rocks are weakly metamorphic and retain much of their character. The grade is generally lower greenschist. Also present in the belt are rhyolite dikes, sandstones and conglomerates. The latter is derived from the metamorphic metadacite of the Series. In addition, numerous felsic and diabase dikes are present.

4

Carolina Slate Belt: Siltstones, tuffs and argillites are metamorphic lithologies of phyllites, slatey phyllites, meta-argillites and quartz-sericite schists, mylonite gneiss, granitic gneiss and "button" schists. This belt is equivalent to the Little River Series and is greenschist grade.

Charlotte Belt: This is a lithology ranging from granite to basic intrusive rocks, volcanic tuffs, ash flows and sediments which have undergone metamorphic change to amphibolites, granitoid gneiss, sillimanite schists, biotite gneiss, sericite-biotite schist, quartzite and gabbro rocks. The grade in the Charlotte belt is almandite-amphibolite facies. Common minerals identified in field study were microcline, mscovite, biotite, oligoclase, most probably andesine, hornblende and kyanite.

Loundesville Belt: These deformed and cataclastic rocks have lost identity with their protoliths. They are augen gneiss, granitoid gneiss, amphibolite, quartz-muscovite schists, "button" schists, talc and quartzose phyllite.

Inner Piedmont: The flank of the Inner Piedmont contains granitoid rocks of quartzofeldspathic origin. Also present are mafic and argillaceous rocks. These lithologies are represented by amphibolite, granitic gneiss sillimanite-mica schist, gneiss and biotitle hornblende gneiss. The grade in the flank portions is generally staurolite-quartz subfacies of almandite-amphibolitefacies. Common minerals identified in field studies along the flank portion include plagioclase, quartz, almandite, staurolite and oligoclase. The core of the Inner Piedmont contains coarse micasillimanite schists, gneiss, feldspar-sillimanite gneiss, biotite granodiorite, augen gneiss and amphibolite. The grade is higher in the core and generally one of upper almandite-amphibolite facies. Common field minerals include sillimanite in sillimanite-almanide-muscovite schist. Also seen are plagioclase, hornblende, biotite and occasional end member garnets (pink) in sillimanite peaks.

Structural Deformation:

The type of structural deformation exhibited in the map area is one of both folding and faulting. The axis of the folds generally run from southwest to northeast as do the strikes of the major fault zones. The dip of the foliation and bedding is quite steep, and it is uncommon to find bedding and foliation planes with less than a 50-degree dip.

The folding style observed in the study area or reported by others is as follows:

In the Belair belt, the style is one of shallow northeast plunging folds with steep isoclinal limbs. Local disruption of the style is due to unknown structural elements. Generally, limbs are steeply dipping to the southeast.

In the Little River Series, the predominant fold style is a series of vertical isoclinal folds with gentle plunge to the northeast. Near zones of penetrative deformation, polyphase folding becomes dominant. Modoc fault zone is an example of this.

The fold style in the Kiokee Belt is fixed by a broad anticline. Northeast limbs have northwest dips while southwestern limbs dip southeast. At the mesoscopic level, rocks have been tightly folded with steep to moderately steep dips. Observed along the northwestern limb, the rocks have undergone polyphase folding. Multiple phases of folding dominate both Slate Belt and Kiokee Belt rocks at their contact.

In the Carolina Slate Belt, Howell and Pirkle (1977) report that top-bottom criteria indicate that a regional syncline with its axis northwest of Parksville, South Carolina, exists in the argillites of the Slate Belt. The axis trends N 50°E and plunges 10°N. Fold styles within the fault zone at Modoc include isoclinal folds, sheared out noses and drag folds. Fold style from Parksville, South Carolina, and to the north flank are typically cylindroidal.

The Charlotte Belt consists of northeast trending southwest plunging assymetrical folds overturned to the west-northwest. Also present are tight northeast striking isoclinal folds. Griffin (1972a) states that in South Carolina the fold style in the Charlotte Belt is problematical because of poor exposure. The style appears to be one of upright folded isoclines.

In the Loundesvillle Belt, Griffin (1972a) believes the folded map pattern is suggestive of general synformal character. Steep dips to the northwest and southeast predominate with cross trends at fold closures. The belt closes out at the Savannah River, where the folds plunge to the northeast at 10 degrees. A cylindroidal fold system with tight upright isoclines is suggested for the belt.

In the Inner Piedmont, Griffin (1972a) shows the attitude of foliation within the Inner Piedmont core to steepen toward the boundary separating it from the southeastern flank. Moderate to steep dips predominate along the core while moderate dips are on the flanks. The core also has locally steeper northwest dips. Griffin suggests a conical fold pattern for the Inner Piedmont.

Measured patterns in the study area suggest that jointing is chiefly related to folding.

Faulting: Table 2 lists mapped faults found in the study area. Occurring in the study area are the three major tectonic fault features of the Brevard Zone, Towaliga-Loundesville-Kings Mountain and the Goat Rock-Modoc fault zones. Many Piedmont geologists have investigated these faults. In addition to the above faults, there occurs within the study area other significant tectonic features identified by Griffin (1972a) as tectonic slides. These slides are observed to mark boundaries or discontinuities in the stratigraphy and lithology. Indication of their existence is seen in slicified breccia zones, abrupt changes in attitude of foliation and discontinuity in metamorphic and lithologic facies.

The Belair Fault located near Augusta, Georgia is an overthrust fault. In this fault, the Belair metavolcanic basement is thrust over the normally overlying Tuscaloosa Formation.

The Patterson Branch Fault is interpreted to be a normal fault.

The Diversion Canal Fault is a shallow angle thrust fault.

The faults in the Lincolnton metadacite and the acid and andesitic pycroclastic sequence are normal faults.